State of Maryland
DEPARTMENT OF NATURAL RESOURCES
MARYLAND GEOLOGICAL SURVEY
Emery T. Cleaves, Director

Educational Series No. 9

Earthquakes in Maryland

by

James P. Reger

1999

Prepared in Co-operation with the Maryland Emergency Management Agency

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EARTHQUAKES IN MARYLAND

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PREFACE

In 1973, the Maryland Geological Survey published a pamphlet about earthquakes and Maryland. Fourteen years later, that out-of-print and out-of-date pamphlet was replaced by a larger pamphlet on the same subject. At the time, that seemed adequate to address general inquiries on the subject. After all, the best available information indicated that Maryland had experienced only 22 very minor earthquakes between 1758 and 1987. An average of about one earthquake per decade did not seem to merit widespread interest, from either the general public or the scientific community. Maryland ranked near the bottom of the list of states in terms of earthquake activity.

However, from January 1990 through December 1996, Maryland experienced 35 small tremors—1 in Harford County, 2 in Cecil County, 3 in Baltimore County, and 29 in Howard County. In only seven years, the number of known earthquakes in Maryland more than doubled. Never in recorded history had Maryland felt so many earthquakes in such a short period of time.

Such a rash of earthquake activity, minor as it was, fostered a new public interest in and some concern about earthquakes. Then, in 1997, the Federal Emergency Management Agency (FEMA) reclassified Maryland from having a low earthquake hazard to a medium earthquake hazard. It seemed only natural that the 1987 earthquake pamphlet should be updated. It soon became apparent that the pamphlet had outgrown its small format. The result is this booklet.

The purpose of this booklet is two-fold: (1) to update the information from the 1987 pamphlet and (2) to provide enough background that the general public has a reasonable understanding of earthquakes, particularly as they relate to Maryland. Thus, it is hoped that this booklet is sufficiently comprehensive so it can stand alone as a fairly elementary to intermediate, understandable discussion of earthquakes in Maryland, while keeping the more technical aspects to a minimum.

ACKNOWLEDGMENTS

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"An earthquake is the way the Earth relieves its stress by transferring it to the people who live on it."

—on a door at Santa Monica College
(cited in Jones, 1994)

Earthquakes in Maryland

by James P. Reger

INTRODUCTION

Earthquakes can be among the most devastating and terrifying of natural hazards. Although floods, tornadoes, and hurricanes account for a greater annual loss in the United States, severe earthquakes pose the largest risk in terms of sudden loss of life and property.

Earthquakes are a greater threat to our pocketbooks than to our lives (Jones, 1994). From 1989 to 1993, the average annual loss in the United States from earthquakes was $1.15 billion, or more than one third of the annual average of $3.3 billion for all natural disasters. The annual average increased to $13 billion for the period 1994-1997, with the Northridge, California earthquake of 1994 costing an estimated $13-20 billion (Source: FEMA Internet site). Two deadly earthquakes occurred in the U.S. in the past ten years. The Loma Prieta (Calif.) earthquake in 1989 killed 66; the Northridge earthquake in 1994 killed 57 (see p. 29).

The study of earthquakes is part of the science of *seismology*, which is the study of shock waves moving through the earth. Especially since the famous San Francisco earthquake of 1906, our knowledge about the composition and structure of the earth's interior has grown greatly. With the passage of the Earthquake Hazards Reduction Act of 1977, there has been much progress in our understanding of earthquake hazards and in risk mitigation. (*Mitigate* means to make less severe.)

EARTHQUAKE CAUSES

An earthquake can be defined as a vibration or trembling of the earth caused by the sudden release of slowly accumulated ***strain*** within the earth's ***crust***. Strain involves deformation, or changing the shape or volume of a body as a result of stress. Stretching a rubber band and bending a piece of wood are examples of strain. As a mass of rock is strained, elastic energy is stored in it in the same way that it is stored in a wound-up watch spring or a stretched rubber band. As the stress increases, the stored-up strain energy also increases until the strength of the rock mass is exceeded, and the rock breaks.

The sudden release of stored strain energy is accompanied by movement along a ***fault*** (Fig. 1), which is a break or fracture along which the rock on one side moves relative to the rock on the other side. Movement along a fault produces the vibrations we know as an earthquake. In general, movement along a fault is assumed to be associated with most earthquakes. Simply stated, if there is an earthquake, then there is a fault that is active.

Once formed, a fault can provide a possible outlet for the building stresses within the earth. In other words, movement may continue, though perhaps sporadically, for thousands or millions of years. However, the sheer weight, or pressure, from the overlying rocks can press the rocks on the two sides of the fault together, in effect creating a

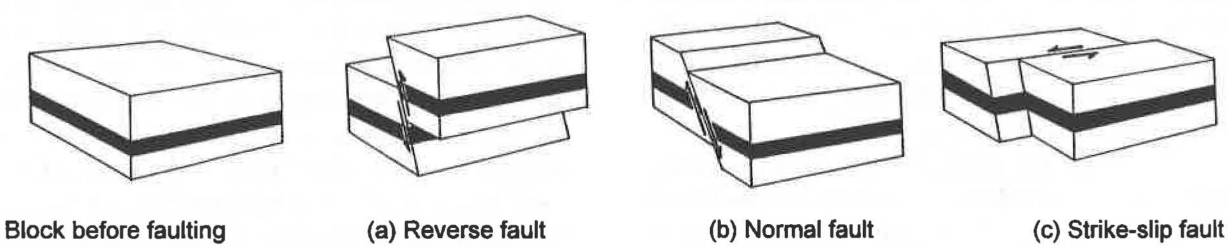

FIGURE 1.— Block diagrams showing creation of and movement along a fault. In these illustrations, the stresses are: (a) compressional, leading to a "reverse fault," in which there is a shortening of the earth's crust accompanied by vertical displacement; (b) tensional, leading to a "normal" fault," in which there is a lengthening of the earth's crust accompanied by vertical displacement; and (c) lateral, leading to a "strike slip" fault, in which there is horizontal displacement.

frictional bond that "locks" the fault. In order for movement to occur along the fault again, external stresses must strain the rock along the fault sufficiently to overcome the frictional resistance. Once the resistance is broken, the accumulated strain energy is suddenly released, thus producing another earthquake.

The process can be compared to storing elastic energy in a rubber band by stretching it. When either the strength of the rubber band or the strength of the fingers' grip on the rubber band is exceeded, that stored strain energy is released suddenly. ("Elastic" means that the deformed object, whether it is a rubber band or a rock, returns to its original shape after the stress is released.) The so-called ***elastic rebound theory*** developed as a result of studies following the 1906 San Francisco earthquake.

This theory is incomplete, however, in that the pressures holding the rocks together along a "locked" fault are so great that the frictional bond on the fault may be stronger than the rock itself. In other words, the rock mass could more easily break somewhere else than slip along the existing fault. Yet there are faults and there are earthquakes associated with them. Perhaps some kind of "lubrication" of the fault is needed to facilitate movement.

The ***theory of plate tectonics*** explains most earthquakes. More than 90 percent of all earthquakes occur in association with boundaries between large, slowly moving, relatively rigid slabs, called ***lithospheric plates***. There are about ten major and several minor plates covering the earth. They are made up of the earth's ***crust*** and upper ***mantle***, collectively called the ***lithosphere***, a term derived from the Greek *lithos*, meaning "stone." These plates range in thickness from 1.6 kilometer (1 mile) under mid-ocean ridges (where new crust forms) to 130 km (80 miles) under old oceanic crust to about 300 km (185 miles) under continents. (For more background on plate tectonics, refer to "Additional Readings" and "Additional Sites on the Internet" on p. 24-25.)

As stated previously, most earthquakes occur when stresses building up within the earth are suddenly released. There are several sources of these stresses, but the major source comes from movement of lithospheric plates. Earthquakes may result when plates attempt to move relative to each other or as the plates move over the relatively plastic part of the earth's mantle, known as the ***asthenosphere*** (from the Greek *asthenos*, meaning "weak"). It is about 180 km (110 miles) thick.

Less than 10 percent of earthquakes occur away from plate boundaries in ***intraplate*** positions (i.e., in a plate's interior). The theory of plate tectonics explains earthquakes along plate margins reasonably well, but it does not explain earthquakes in plate interiors—often referred to as the "stable continental interior." Although rare, major earthquakes capable of producing ground rupture have occurred in stable continental interiors around the world (Machette and Crone, 1993).

Although earthquakes, whether at plate boundaries or in plate interiors, are associated with movement along faults, they can also be triggered by volcanic activity, by very large landslides, and by some types of human activity.

In intraplate areas not known for frequent earthquakes (e.g., Maryland), pinpointing the cause of the rare tremor is very difficult. It may be possible (although rarely) to locate a fault along which movement is occurring, and it may be possible to determine some characteristics of that movement, but it may not be possible to explain why such movement along a fault is occurring.

The North American continent basically lies on the western half of the North American lithospheric plate (Fig. 2). The Pacific coastline roughly coincides with the boundary between the North American and the Pacific plates, which explains why the western U.S. has so many earthquakes. However, the eastern boundary of the North American Plate lies approximately down the middle of the Atlantic Ocean along what is known as the Mid-Atlantic Ridge. Maryland, therefore, lies well within the interior of the North American Plate.

Ancient faults in stable continental interiors are difficult to evaluate as geologic hazards. The historical earthquake record is too short and too incomplete to precisely determine rates of earthquake occurrence in most of these regions. Studies suggest (1) that large earthquakes may occur on intraplate faults that have not produced major earthquakes for tens of thousands of years, and (2) that moderate earthquakes may also occur on intraplate faults that have experienced relatively few, low-level earthquakes. These characteristics compound the problem of identifying intraplate faults that may be associated with destructive earthquakes (Machette and Crone, 1993).

Relatively little is known about the causes of earthquakes in the eastern United States. Although eastern earthquakes tend to occur in distinct zones, there is often no clear association among earthquake occurrence, known geologic structures (such as known active faults), and surface displacement. This is in contrast to the western U.S. (Hanks, 1985), which lies near a plate boundary. Seismologists now realize that damaging earthquakes in the East may be generated by small faults that do not reach the surface and that geological and geophysical investigations may not detect (Seeber and Armbruster, 1988).

Researchers have measured the plate tectonic stresses in the broad intraplate region of the North American plate. Eastern North America and possibly much of the western North Atlantic is under a uniform compressive stress oriented, on average, ENE-WSW. This is nearly parallel to the WSW direction of absolute plate motion (Fig. 2). Reverse faulting (Fig. 1) dominates under these conditions (Benson, 1993, *after* Zoback and Zoback, 1989, 1991).

A local variation in the stress field is found in Maryland, eastern Virginia, and possibly northern Delaware, where reverse faults of Miocene and younger age indicate apparent northwest-southeast compression (Benson, 1993).

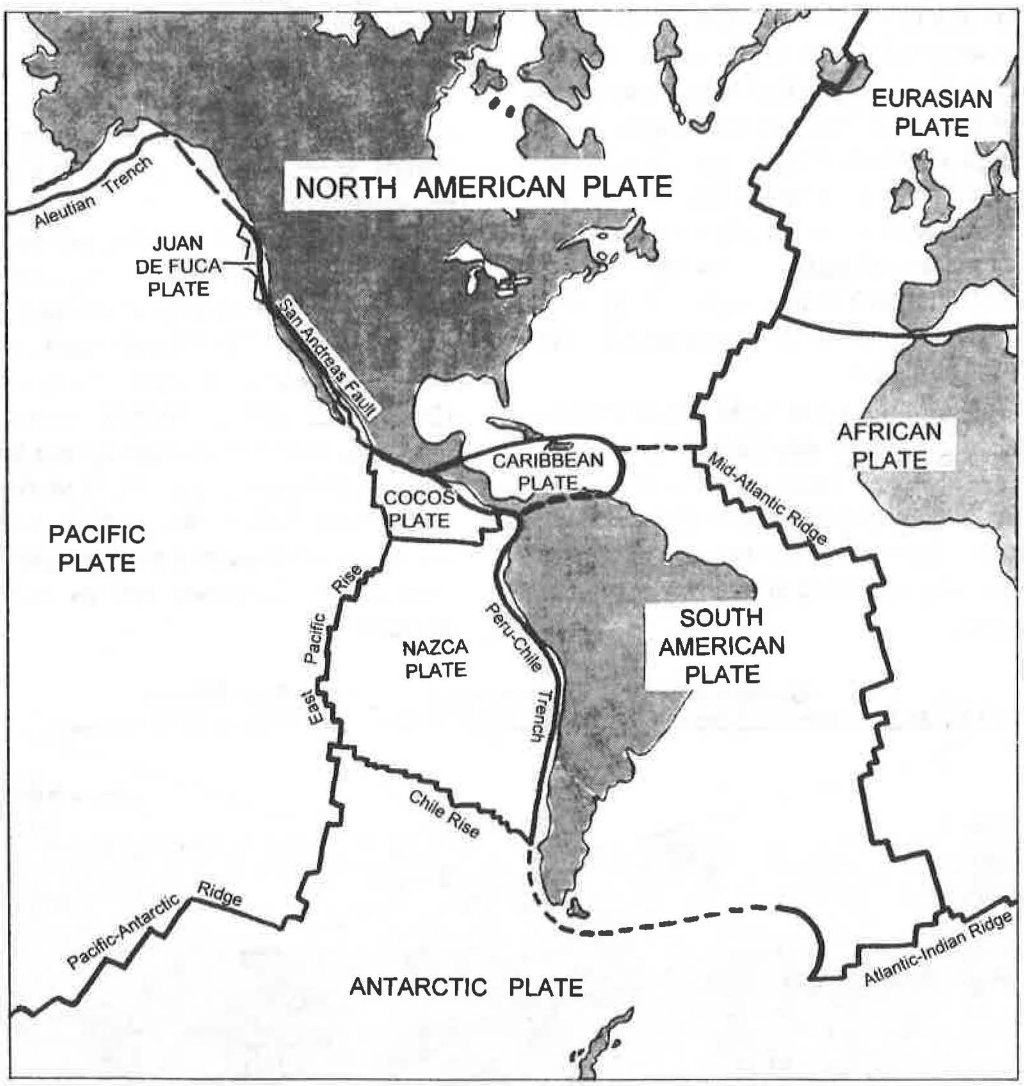

FIGURE 2.— Map showing the North American continent relative to the North American lithospheric plate. Notice that the west coast of the continent lies at or near the western boundary of the plate, but that the East Coast lies far from the eastern boundary along the Mid-Atlantic Ridge.

BASIC EARTHQUAKE MECHANICS

The sudden release of stored strain energy causes movement of the earth's crust along ***faults***, which in turn generates ***elastic*** shock waves, or ***seismic waves*** (Fig. 3). These shock waves radiate in three dimensions from the point of origin, known as the ***focus***, or ***hypocenter***, much as ripples radiate outward in two dimensions when a pebble is dropped into a pond. The point on the earth's surface directly above the hypocenter is called the ***epicenter*** and is generally the site on the earth's surface where seismic waves first arrive.

Approximately 85 percent of earthquakes are "shallow"—that is, having focal depths of less than 70 kilometers, or 40 miles. This may not seem very shallow, but if one considers the earth's radius of approximately 6,400 km (3,960 miles) and the fact that the deepest earthquakes have focal depths of 700 km (400 miles), 70 km is relatively shallow. In the southeastern United States, for example, the average focal depth is about 13 km, or about 8 miles (Sibol and others, 1996). The mechanism for most "shallow" earthquakes probably involves fracturing of brittle rock in the crust or the relief of internal stresses due to frictional resistance locking opposite sides of a fault.

Regardless of the focal depth, an earthquake generates several types of seismic waves, or elastic shock waves (Fig. 3). There are two basic types: ***body waves***, which are generated at the focus and travel through the body of the earth, and ***surface waves***, which are generated at and travel near the earth's surface.

There are two types of body waves: the faster moving ***primary wave***, or ***P wave***, and the slower ***secondary wave***, or ***S wave***.

The P wave is a "compressional wave," which means that it alternately pushes and pulls the rock as the wave form moves through the earth. This "push-pull" vibration is in the same direction as the P wave moves (Fig. 4a). It is the "pull" part of the motion that defines the wave as elastic, because the rock is returning to its original position after the stress of the "push" part of the wave. The push-pull movement is similar to the way sound waves move through matter.

In contrast, the S wave is a "shear wave," which shakes, or "shears," the rock at right angles to the wave's path (Fig. 4b). The up-and-down and side-to-side motion in the earth shakes the earth's surface both vertically and horizontally. That is why S waves can be so damaging to buildings and other structures. S waves cannot pass through liquids, such as the earth's molten outer core and the world's oceans.

Body wave velocities are not constant, varying with rock properties. In strong surface rocks like granite, a typical velocity of P waves is about 4.8 to 5.5 km/sec (10,700-12,300 mph), and the typical velocity of S waves is about 3 km/sec (6,750 mph) (Bolt, 1982; 1993). Both P waves and S waves tend to accelerate (increase speed) with increasing distance from the focus. Their velocities also vary with depth below the earth's surface, as the properties of the earth's interior vary—increasing as rock density increases and as rock temperature decreases.

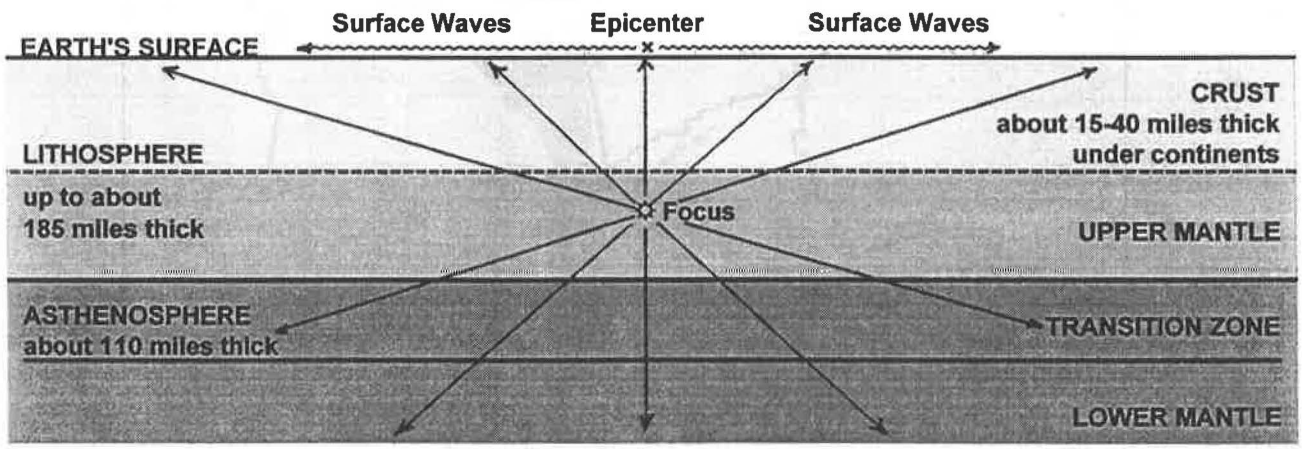

FIGURE 3.— Simplified cross section of the earth's lithosphere (crust and upper mantle) and the asthenosphere, depicting body waves ——, surface waves ~~~~, an earthquake focus ☼ (hypocenter), and an epicenter ×. (not to scale)

Body waves are reflected and refracted (bent), altering their paths and velocities, as they encounter the various layers that make up the earth—continental and oceanic crust, upper and lower mantle, and outer and inner core, not to mention the variety of rock types encountered in the crust alone. This results in the body waves following numerous paths to arrive at a *seismometer* (the instrument that detects the seismic waves), which leads to the differentiation of different "phases." The greater the distance between earthquake and seismometer, the more phases, or waveforms, arrive at the seismometer. These and other differences in the characteristics of P and S waves (such as the inability of S waves to pass through liquids) have provided much information about the composition and structure of the earth's interior, as well as about earthquakes.

What happens when body waves reach the earth's surface? Aside from the possible conversion of part of the P waves to audible sound waves, which can create a "boom," part of a P wave can also be converted to S-wave motion. And, as already stated, part of the S wave transfers its energy into shaking of buildings and other structures. However, most of the energy of P and S waves is reflected back down into the earth's crust, so that the surface is affected almost simultaneously by upward-moving and downward-moving body waves. For this reason, the amplitude (height) of body waves increases near the surface; sometimes doubling the amplitude of upcoming waves. This additive effect enhances potential for shaking damage at the earth's surface (Bolt, 1993).

Differences in the velocities of P and S waves are crucial in determining the time of occurrence and the epicenter of an earthquake. Because P waves travel faster than S waves, the greater the distance between a seismometer and the epicenter, the greater the time difference between the arrival of the first P wave and the first S wave at a seismometer. This time differential, coupled with P- and S-wave velocities, can be used to calculate the distance between seismometer and earthquake. Using data from at least three seismometers at different locations (a seismometer is the instrument that detects the seismic waves), one can determine the actual location of the earthquake's epicenter. (The interested reader who has access to the Internet may want to go the Virtual Earthquake site listed in the references on pages 24-25. This site leads you through an exercise to actually determine local magnitudes and epicenters.)

The second basic type of earthquake wave is the *surface wave*. These originate at and travel only along the earth's surface. Their wave forms die out quickly with depth. Two main types of surface waves have been identified: ***Love*** waves (or L waves) and ***Rayleigh*** waves (or R waves).

Love waves move at a velocity roughly nine-tenths that of S waves. A Love wave's motion (Fig. 4c) is basically similar to the horizontal component of an S wave, shaking the ground and buildings with horizontal forces. Thus, Love waves are particularly damaging to building foundations (Bolt, 1993).

Rayleigh waves generally travel more slowly than Love waves. The motion associated with a Rayleigh wave is somewhat similar to the roughly circular "rolling" motion of ocean waves, moving both vertically and horizontally in a vertical plane that is parallel to the direction of wave movement (Fig. 4d).

Noise is often associated with earthquakes. Many people describe major earthquakes as very noisy, using words like rumbling and dull roar. In small earthquakes, such as have occurred in Maryland, the noise tends to be more of a "boom."

What causes the noise? When compressional P waves reach the earth's surface, part of their energy may be converted to sound energy that will be transmitted through the air. The first waves that carry the earthquake shaking through the ground are sound waves, which are also compressional. However, the frequency of this wave is below the range of human hearing unless you are right on top of the earthquake. (The higher frequencies die off with distance more quickly than the lower frequencies, just as you hear a low pitched noise at a greater distance than a high pitched noise. This is also why nearby earthquakes feel jerky while distant earthquakes produce a rolling motion.) The noise heard in an earthquake is usually from buildings that vibrate at a higher frequency than the ground that set them creaking. The perception of noise a few seconds "before" an earthquake is usually buildings creaking in response to the P-wave (Jones, 1994).

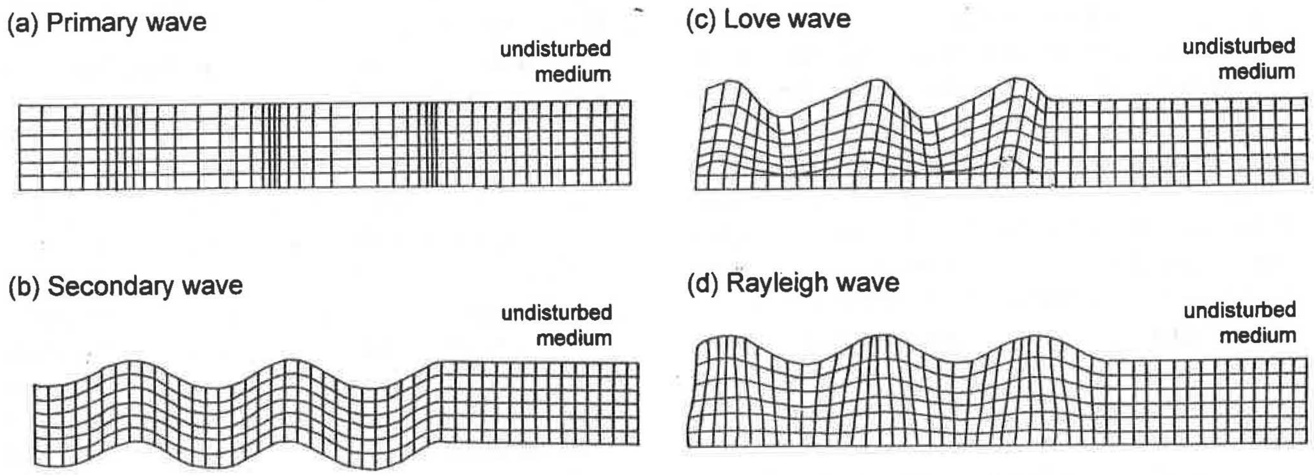

FIGURE 4.– Cross-section diagrams illustrating the nature of ground motion near the earth's surface in four types of seismic waves. In each diagram, the wave form is moving from left to right. (after Bolt, 1993)

FACTORS DETERMINING DAMAGE

There are many interrelated factors that determine the extent of loss of property and life from an earthquake. Each of the following should be prefaced with "other factors being equal...."

- **Amount of seismic energy released**: Related to the amount of slip along a fault, the greater the energy released, the greater the potential damage. Historically, Maryland's earthquakes involve low energy releases.
- **Attenuation of seismic waves**: The "dying out" of shock waves by natural reduction in wave *amplitude* over distance traveled from the epicenter is related to the regional geology. The lower the attenuation, the greater the "felt area," and thus the potential for damage.
- **Duration of shaking**: This is one of the most important aspects of ground motion for causing damage. The longer the period of shaking, the greater the potential for losses. Most of Maryland's earthquakes have involved nothing more than a "jolt" of 1-2 seconds, rather than a shaking duration of many seconds.
- **Depth of focus, or hypocenter**: The shallower the focus (the point of an earthquake's origin within the earth), usually the greater the potential for destructive shock waves reaching the earth's surface. Stronger events at much greater depths typically produce only moderate shaking at ground level. Maryland's earthquakes generally are very shallow—3 to 5 miles.
- **Distance from a known active fault**: There is a common misconception that most damage occurs near the earthquake's epicenter (the point on the ground directly above the focus). However, the epicenter is typically not the point where most damage occurs. Proximity to the fault along which movement has occurred is a better predictor of ground-shaking intensity. In the absence of a known fault, the distance from the epicenter serves as a second-best alternative.
- **Geologic setting**: Different foundation materials exhibit different responses to seismic vibrations. For example, in soft unconsolidated material, earthquake vibrations last longer and develop greater amplitudes, which produce more ground shaking, than in areas underlain by bedrock.
- **Geographic and topographic setting**: This characteristic relates more to secondary effects of earthquakes than to primary effects such as ground shaking, ground rupture, local uplift and subsidence, and liquefaction. Secondary effects include fires (from broken gas and electric lines); landslides (generally in hilly or mountainous areas); seismic sea waves, or tsunamis (restricted to oceans and coastal areas).
- **Population and building density**: As these increase in the area around fault movement, the damage potential increases.

- **Types of buildings**: Wooden frame structures tend to respond to earthquakes better than do more rigid brick or masonry buildings. Taller buildings are more vulnerable than one- or two-story buildings when located on soft, unconsolidated sediments, but taller buildings tend to be the more stable when on a hard bedrock.
- **Building codes**: Areas where destructive earthquakes are relatively common are more likely to have earthquake-resistant design standards in building codes, which will reduce damage. Although Maryland subscribes to the BOCA (Building Officials and Code Administrators, Inc.) National Building Code, it does not currently apply the seismic provisions in the code.
- **Time of day**: Timing has virtually no effect on property damage, but experience shows there are fewer casualties if an earthquake occurs in evening or early morning, because most people are at home and awake--thus in an optimum position to respond properly.

With so many factors involved, it is no wonder that being site-specific about probable damage is very complex.

MEASURING EARTHQUAKES

The vibrations produced by earthquakes are detected by instruments called ***seismometers*** and recorded by instruments called ***seismographs*** to produce recordings called ***seismograms***. (An analogy is a microphone, a tape recorder, and a tape.) The time of occurrence, duration of shaking, locations of the epicenter and focus, estimates of the energy released, and other information can be determined from seismographic data.

For many years, there were no seismograph stations operating in Maryland. Then in 1995, the joint efforts of the Maryland Geological Survey, Howard County (Maryland) Government, the U.S. Nuclear Regulatory Commission, and Lamont-Doherty Earth Observatory (part of Columbia University in New York), established a digital seismograph station in Howard County. The Maryland Geological Survey continues to receive technical and scientific assistance from Lamont Doherty and the Delaware Geological Survey. Other seismograph stations in the region include several in Delaware; one in Millersville, Pa.; one in State College, Pa.; two in Morgantown, W.Va.; and several in central and southwestern Virginia.

The size or severity of an earthquake is expressed in several ways, the two most common being ***intensity*** and ***magnitude***.

Intensity, which is reported on the Modified Mercalli Intensity (MMI) Scale as revised in 1931, is based on eyewitness accounts and observations (Table 1). Intensities are ranked with Roman numerals on a 12-level scale and range from barely perceptible (I) to total destruction (XII). The lower intensities (I-VI) are described in terms of people's reactions and sensations, which can vary and are fairly subjective. The higher intensities (VII-XII) relate chiefly to observable damage, which makes them more objective.

Much has changed since 1931, and the Modified Mercalli Intensity scale needs to be revised or updated to reflect developments in areas such as manufacturing and building methods (Stover, 1989).

Magnitude is an objective measure of earthquake severity and is closely related to the amount of seismic energy released at the earthquake focus.

California seismologist Charles Richter developed the magnitude scale in 1935 to quantify local (California) earthquakes occurring within 100 km (approximately 62 miles) of a standardized seismometer. It is called "local magnitude" (symbol M_L) because Richter developed the scale for use with local earthquakes.

Today, there are several methods for determining and calculating magnitude. One uses body waves, two use various surface waves, and still others use other seismic attributes. The most recently adopted is ***moment magnitude*** (see the Glossary, p. 34).

Moment magnitude is related to the total energy released in the earthquake. Because it may be determined from certain field measurements, moment magnitude can be calculated for some old earthquakes that pre-date modern seismographs.

Which magnitude is utilized depends on the properties of the seismic waves for a particular earthquake, on the distance between the epicenter and the particular reporting seismograph, and on whether there is surface rupture. Moment magnitude is difficult to determine unless one can measure the amount of slip on the fault and the areas of the fault surface.

The differences in results among the various methods of determining magnitude are usually

slight—a few tenths of a point. Strictly speaking, the "Richter magnitude" refers only to "local magnitude" and should be distinguished from the other types of magnitudes.

Regardless of how magnitude is determined, the standard scale is the Richter Scale, an open-ended scale expressed in whole numbers and decimal fractions. The Richter Scale is logarithmic, meaning that an increase of one magnitude represents a tenfold amplification of the ground motion. For example, a magnitude 5 earthquake has 10 times the wave amplitude, or ground motion, of a magnitude 4 and 100 times the wave amplitude of a magnitude 3 event. However, that does not mean that a magnitude 5 event is 10 times stronger than a magnitude 4.

TABLE 1.— The Modified Mercalli Intensity Scale of 1931 (abridged).

MMI	Description
I	Not felt except by very few people under especially favorable conditions. Sometimes birds and other animals reported uneasy or disturbed; sometimes doors may swing very slowly.
II	Felt by a few people, especially those on upper floors of buildings. Sometimes hanging objects may swing; same effects as in grade I may be observed.
III	Felt quite noticeably indoors. Many do not recognize it as an earthquake. Motion usually rapid vibration, sometimes similar to that due to passing of a heavy truck. Standing motor-cars may rock slightly. Hanging objects may swing slightly.
IV	Felt by many who are indoors; felt by a few outdoors. At night, some awakened. Dishes, windows and doors rattle. Sensation like heavy body striking building or falling of heavy objects inside. Standing vehicles rock noticeably.
V	Felt by nearly everyone; many or most awakened. Some dishes and windows broken; some cracked plaster; some cracked windows possible, but not usually; hanging objects and doors swing considerably; unstable objects overturned.
VI	Felt by everyone, indoors and out; many frightened and run outdoors. Some heavy furniture moved; some fallen plaster or damaged chimneys; broken dishes in considerable quantity; some windows. Damage slight in poorly built buildings.
VII	Most people alarmed and run outside. Some may find it difficult to stand. Noticed by persons driving cars. Waves on ponds, lakes; some sandy stream banks may cave in. Damage negligible in well constructed buildings; considerable damage in poorly constructed buildings. Heavy furniture overturned. Many windows broken.
VIII	Damage slight in specially designed structures; considerable in ordinary buildings; great in poorly built structures. Very heavy furniture overturned. Chimneys, monuments, etc. may topple.
IX	Damage considerable in specially designed structures. Buildings shift from foundations and collapse. Ground cracked. Underground pipes sometimes broken.
X	Severe damage to well-built wooden structures; some destroyed. Most masonry structures destroyed. Ground badly cracked. Landslides on steep slopes. Damage serious to dams, dikes.
XI	Few, if any, masonry structures remain standing. Railroad rails bent; bridges destroyed. Broad fissures in ground. Buried pipelines out of service.
XII	Virtually total destruction. Waves seen on ground; objects thrown into the air; rivers deflected; ground-water flow changed greatly.

TABLE 2.— Magnitude versus ground motion and energy (National Earthquake Information Center Internet web site, 1998).

Magnitude Change	Ground Motion Change (Displacement)	Approximate Energy Change
1.0	10.0 times	32 times
0.5	3.2 times	5.5 times
0.3	2.0 times	3 times
0.1	1.3 times	1.4 times

TABLE 3.— Approximate relationships among earthquake magnitude, intensity near the epicenter, worldwide occurrence, and area affected (after Spence and others, 1989; National Earthquake Information Center Internet web site, 1998).

General Description	Richter Magnitude	Modified Mercalli Intensity	Expected Annual Incidence	Distance Felt[1] (miles)	Felt Area[1] (sq. mi.)
Microearthquake	< 2.0	–	>2,000,000	–	–
Very Minor	2.0-2.9	I-II	350,000	–	–
Minor (Felt generally)	3.0-3.9	II-III	49,000	15	750
Light	4.0-4.9	IV-V	6,000	30	3,000
Moderate	5.0-5.9	VI-VII	1,000	70	15,000
Large (Strong)	6.0-6.4	VII	210	125	50,000
	6.5-6.9	VIII	56		
Major (Severe)	7.0-7.4	IX	15	250	200,000
	7.5-5.9	X	3.1		
Great	8.0-8.4	XI	1.1	450	640,000
	8.5-8.9	XII	0.3		

[1]Distance felt relates to wave attenuation, which varies regionally.

TABLE 4.— Damaging (M > 5) historical earthquakes in the eastern U.S. (adapted from Stover and Coffman, 1993).

Date	Location	Magnitude[1]	Intensity	Comments
1811-1812	New Madrid, Mo.	7.8-8.3 8.4-8.7[2]	X-XII	felt 2,000,000 mi^2; 4-5 quakes M≈8±
1875	Goochland Co., Va.	5.0	VII	felt >50,000 mi^2
1884	near New York City	5.3	VI	felt from New Hampshire to Baltimore.
1886	Charleston, S.C.	6.5-7	IX-X	60 lives lost
1897	Giles County, Va.	5.8	VII-VIII	felt >280,000 mi^2 in 13 states
1937	Anna, Oh. (western Ohio)	5.0	VII-VIII	felt >150,000 mi^2

[1] Estimated on the basis of felt area and Modified Mercalli Intensity. The Richter Scale was not used until 1935.

[2] The two ranges in magnitudes shown here exemplify the different methods of determining magnitude.

As a first approximation, each whole number increment on the Richter Scale corresponds to a release of about 31 to 32 times more seismic, or vibrational, energy. Thus, for example, a magnitude 5 releases about 32 times the energy of a magnitude 4, and about 1,000 times (or 32 × 32) the energy of a magnitude 3. The general relationship among magnitude, ground motion, and energy is shown in Table 2.

In theory, the Richter Scale has neither a lower nor upper limit. However, the strength of earth materials limits magnitude for practical purposes to less than 10. Very small earthquakes can have negative magnitudes ($M<0$).

The world's largest recorded earthquake occurred off the coast of Chile in western South America in 1960, and had a moment magnitude of 9.5 (Appendix 3). By comparison, the largest historical U.S. earthquake (ranking second worldwide) occurred in 1964 near Anchorage, Alaska and had a moment magnitude of 9.2 (Appendix 2 and 3).

Although there is a rough relationship between the Modified Mercalli and the Richter scales (Table 3), the relationship varies with local geologic conditions. In general, damage is slight at magnitude 4.5, becomes moderate at about 5.5, and above 6.5 can range from considerable to nearly total (Bollinger and others, 1989).

EARTHQUAKES IN THE REGION

When people think of earthquakes, most tend to think of Southern California or the western United States. Indeed, of the 30 strongest earthquakes in U.S. history, 10 were in Alaska, 10 were in California, and 5 were in other western States (Appendix 2). Even though the vast majority of earthquake activity in the United States occurs west of the Rocky Mountains, earthquakes also occur in the central and eastern U.S. (It might be noted that many earthquake seismologists often define "eastern U.S." as the area east of the Rocky Mountains — i.e., roughly the eastern two-thirds of the country.)

Although the eastern U.S. has experienced damaging earthquakes in historical time (Table 4; Appendix 1), only the most active areas have been studied in detail. The greatest seismic event ever to occur in the continental U.S. in historical times was a series of earthquakes that shook the mid-continent around New Madrid, Missouri, in the winter of 1811-1812 (Table 4). Estimates of the magnitude range as high as 8.7; estimated maximum intensity was XII; and the felt area, which included Maryland, was 2 million square miles.

The mid-Atlantic and central Appalachian region, including Maryland, is characterized by a moderate amount of low-level earthquake activity, but the causes of earthquakes can be largely a matter of speculation. In Maryland, for example, there are many faults, but no particular fault is known or suspected to be active. Because of the relatively low seismic energy release, this region has received relatively little attention from earthquake seismologists (Bollinger, 1969).

In the Atlantic Coastal Plain, it is now thought that earthquakes may be associated with nearly vertical faults that formed during the break-up and rifting of the "supercontinent," Pangaea during the late Triassic to middle Jurassic periods about 220 to 175 million years ago (Hanks, 1985). Such faults would occur in the "basement" bedrock, and not in the overlying, younger Coastal Plain sediments themselves.

Recent evidence suggests that earthquakes in the Ridge and Valley Province and in the Piedmont Province occur at shallow depths (usually less than 15 miles) in the Precambrian crystalline basement and lower Paleozoic sedimentary rocks (Wheeler and Bollinger, 1984; Richard Benson, written communication, 1998). The geologic structures that may be responsible for earthquake activity in these areas are preexisting zones of very low angle reverse faults (thrust faults) that formed during continental collisions and closing of a proto-Atlantic Ocean during the Paleozoic era roughly 300-500 million years ago (Rankin, 1975). It is also possible that some earthquakes in the Piedmont are in some way related to igneous dikes that were intruded into surrounding bedrock during continental rifting (splitting apart) in the Triassic and Jurassic periods (roughly 220-175 million years ago).

The last earthquake in the eastern United States to cause appreciable damage occurred in 1886 near Charleston, South Carolina (Table 4; Appendix 1). It had an estimated magnitude of 6.5-7, an intensity of X, and was felt over an area of 2 million square miles. Even in Maryland, the felt intensity from this earthquake was IV-V (Nuttli and others, 1986).

Closer to Maryland, damaging earthquakes include an intensity VIII event near Boston in 1755 and intensity VI-VII events near New York City in 1737 and 1884 (Stover and Coffman, 1993).

Figure 5 presents two time frames of earthquake in the eastern United States and Canada. Figure 5a shows the locations reported in the U.S. Geological Survey's monthly and weekly listing of epicenters for the period January, 1990 through October, 1998. Generally, the USGS listings do not include earthquakes having a magnitude less than about 2.5. Figure 5b shows known earthquakes of magnitudes greater than 4.5 that occurred between 1568 and 1989. The maps show similar clusters of epicenters that mark the areas of highest seismicity—e.g., the New Madrid Seismic Zone in southeastern Missouri, western Kentucky, western Tennessee, and southern Illinois; eastern Tennessee; southwestern Virginia; central Virginia; and southeastern Pennsylvania. Although numerous, these earthquakes are generally very minor. For example, the entire southeastern U.S. (Maryland, Delaware, Virginia, West Virginia, eastern Kentucky, eastern Tennessee, North Carolina, South Carolina, Georgia, Florida, and Alabama) experiences an average of 30 tremors per year of magnitude 2 (too small to be listed by the U.S. Geological Survey), 3 tremors per year of magnitude 3, and less than one half tremor per year of magnitude 4 (Chapman and others, 1997).

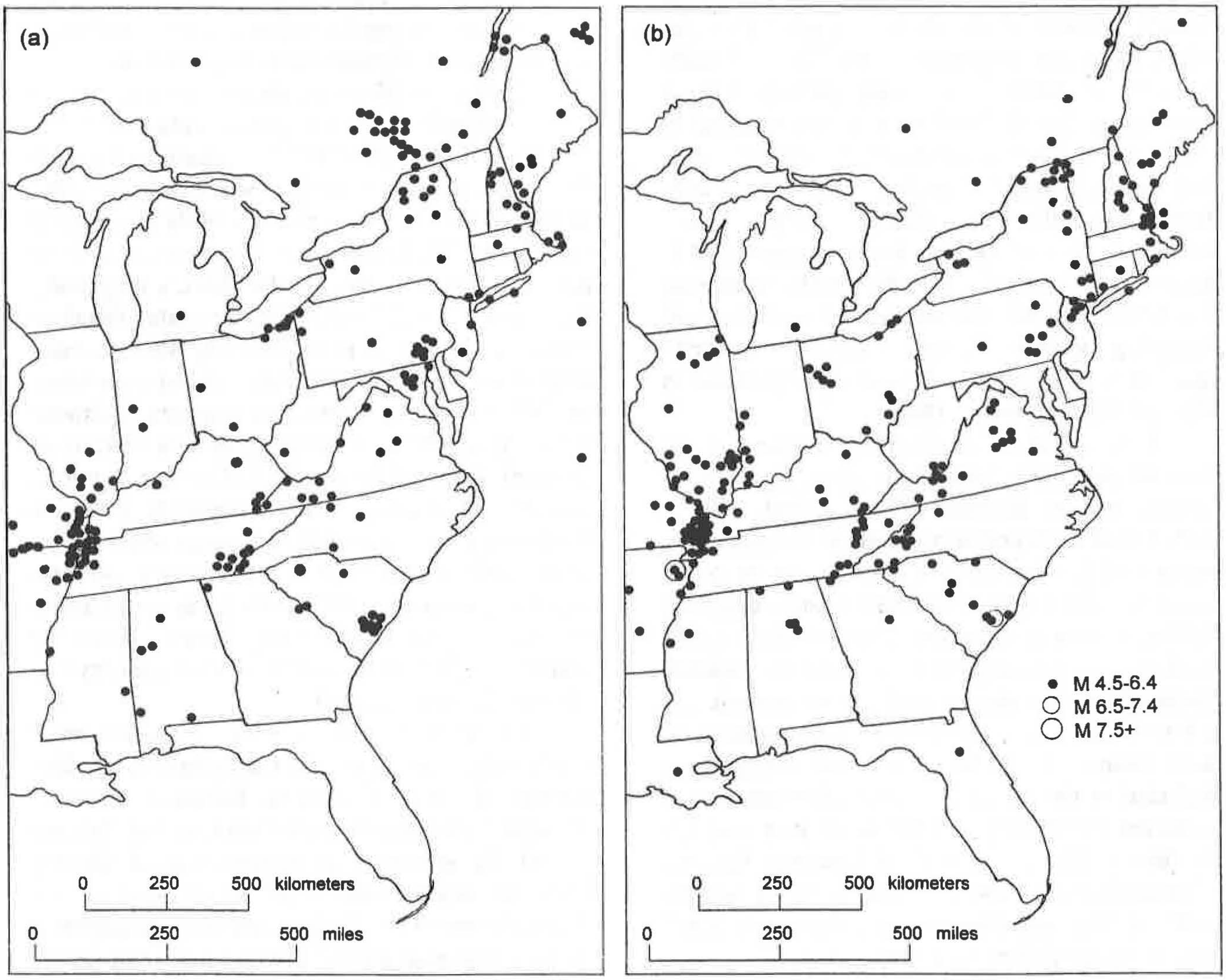

FIGURE 5.— Earthquake epicenters in the eastern United States and Canada. **(a)** Magnitudes M ≥ 2.3 from January, 1990, through October, 1998 (compiled from monthly and weekly listings of *Preliminary Distribution of Epicenters* of the National Earthquake Information Center); **(b)** magnitudes M ≥ 4.5 (estimated or instrumented) between 1568 and 1989 (from Stover and Coffman, 1993).

Maryland is one of only two states (the other being Wisconsin) that have not had an earthquake with a magnitude ≥4.5 occur within their borders during the period of historical record (Stover and Coffman, 1993; also see Fig. 5b).

Several earthquakes in adjacent states, most often southeastern Pennsylvania, have been felt in Maryland. The strongest out-of-state earthquake to be felt in parts of Maryland in recent years occurred Easter Sunday, April 22, 1984. It was reportedly felt in eight states and the District of Columbia, over an area of approximately 19,000 square miles. Centered about 12 miles south of Lancaster, Pennsylvania, this earthquake registered 4.1 on the Richter Scale and had an epicentral intensity of V to VI. Most notable effects in Maryland were in the northeastern part of the state, which generally experienced Modified Mercalli Intensity V effects. Hanging pictures fell in Conowingo (Cecil County); windows cracked in Elkton (Cecil County) and Joppa (Harford County); and standing vehicles rocked slightly in Union Bridge (Carroll County) (Stover, 1988). A 3.0-magnitude tremor four days earlier is considered to have been a *foreshock*. Ten *aftershocks* registering 2 to 2.5 magnitude occurred over a four-day period following the April 22 event. The Lancaster earthquake is likely related to Triassic-age structures in the area (Scharnberger, 1984).

In historical times, Maryland's seismicity has been among the lowest of the states in the Mid-Atlantic region. Between 1758 and 1991, only 25 very minor earthquakes occurred in Maryland—an average of less than one every ten years (Fig. 6 and Table 5). The degree of accuracy of these epicenter determinations is such that a few of these earthquakes may actually have occurred in adjacent states, and for the same reason it is conceivable that a few of the closer out-of-state earthquakes could have occurred within Maryland. For example, not included in the list of 25 was a minor shock that occurred on January 2, 1885 in an area near the Frederick County, Maryland-Loudoun County, Virginia border. The maximum intensity was V, with the total felt area covering more than 3,500 square miles (Bollinger, 1969).

Of the Maryland earthquakes through 1991, 2 occurred in the Ridge and Valley Province (Western Maryland), 13 were in the Piedmont Province (Central Maryland), and 10 were in the Coastal Plain Province (Southern and Eastern Maryland). As we shall see, those numbers would change beginning in 1993.

The first reported earthquake to have actually had its epicenter in Maryland occurred south of Annapolis on April 25, 1758, but no record of its strength is known to exist. The shock lasted 30 seconds and was preceded by subterranean noises. Additional felt reports were received from a few points in Pennsylvania (National Earthquake Information Center, 1973). Maryland's strongest confirmed tremor was a 3.1-magnitude event near Hancock, Washington County, in 1978. That perhaps was rivaled in 1939 by an intensity V event (unknown magnitude) near Phoenix, Baltimore County (Table 5). Earthquakes of such magnitudes or intensities are considered to be minor, and very seldom result in significant damage or injury.

Until 1990, Maryland had averaged one small tremor roughly every ten years. Then in 1990-1991, central Maryland felt three small earthquakes in roughly the same location, which suggests they may have been related. The first of these occurred on January 13, 1990. According to reports from nine seismograph stations, the shock's magnitude registered 2.5 to 2.6 on the Richter Scale. Depth to focus was estimated to be 2 miles, which is considered very shallow. Intensities ranged from intensity V in the Randallstown area (western Baltimore County); to IV at Eldersburg (southern Carroll County), Ellicott City (northern Howard County), Granite, Hernwood, and Woodstock (western Baltimore County); and III at Owings Mills (a few miles north in western Baltimore County). Several first-hand accounts of the event from the Granite-Hernwood area reported that houses shook or windows rattled, both indicative of an intensity IV. No damage was reported.

On April 4, 1990, reports of another small earthquake came from the Randallstown-Granite-Hernwood area of western Baltimore County. However, seismic stations in Delaware and Virginia placed the epicenter in western Carroll County (Fig. 6), approximately 20 miles west of the Randallstown area. Such an apparent discrepancy is not uncommon where areas are not covered by a regional network of seismographs. In such cases, felt reports are considered more reliable than seismograph data. By all accounts, this event was smaller than the January tremor. The magnitude

was determined to be only 1.6 to 1.7, and first-hand accounts of a few local residents suggested a Modified Mercalli Intensity of about II or III. One eyewitness described the event as starting with the sound of distant thunder, getting louder for about 25 seconds, then followed by 5 to 7 seconds of minor rumbling or shaking. Another local resident reported nearly two dozen similar events, although not confirmed as earthquakes, between October, 1987 and May, 1990.

In 1993, Howard County experienced a first in Maryland earthquake history. From March through December, neighborhoods near Columbia, which is about midway between Baltimore and Washington, D.C., experienced 21 microearthquakes (i.e., magnitude <2.0) and 5 very minor earthquakes (magnitude 2.0-2.7) (Fig. 6 and 7, Table 5). Seismologists from Columbia University's Lamont-Doherty Earth Observatory in New York arrived to set up a temporary network of seismometers to monitor and investigate the activity. Within a few days, public interest turned to public concern, as several press conferences, town meetings, and numerous radio and television interviews tried to answer questions.

Not only was the occurrence of a *swarm* of very small tremors new to Maryland, these events generally were felt more strongly and over a wider area than their magnitudes would suggest. Modified Mercalli Intensities were as high as IV or V, which is not the norm for the magnitudes (maximum 2.7, most less than 1.5). Some were felt by a few people under ideal circumstances as far away as 15 to 20 miles, in suburbs of Baltimore and Washington, D.C.

The explanation was very shallow hypocenters. Lamont-Doherty seismologists calculated focal depths on the order of 1,500-1,600 feet. In general, some seismologists report focal depths in the Piedmont Province (in which these and most Maryland earthquakes occur) of 10 to 12 kilometers (6-7.5 miles); others locate hypocenters only to 6 kilometers (about 3.7 miles); and others argue for 2 kilometers (1.2 miles) or less (Bollinger and others, 1991).

Lamont also calculated the position of a buried reverse fault along which slippage occurred, but the cause of the movement remains unknown. The NW-SE orientation of the fault is consistent with WSW direction of absolute plate motion, but is at odds with the local variation in stress field reported for Maryland (see page 3).

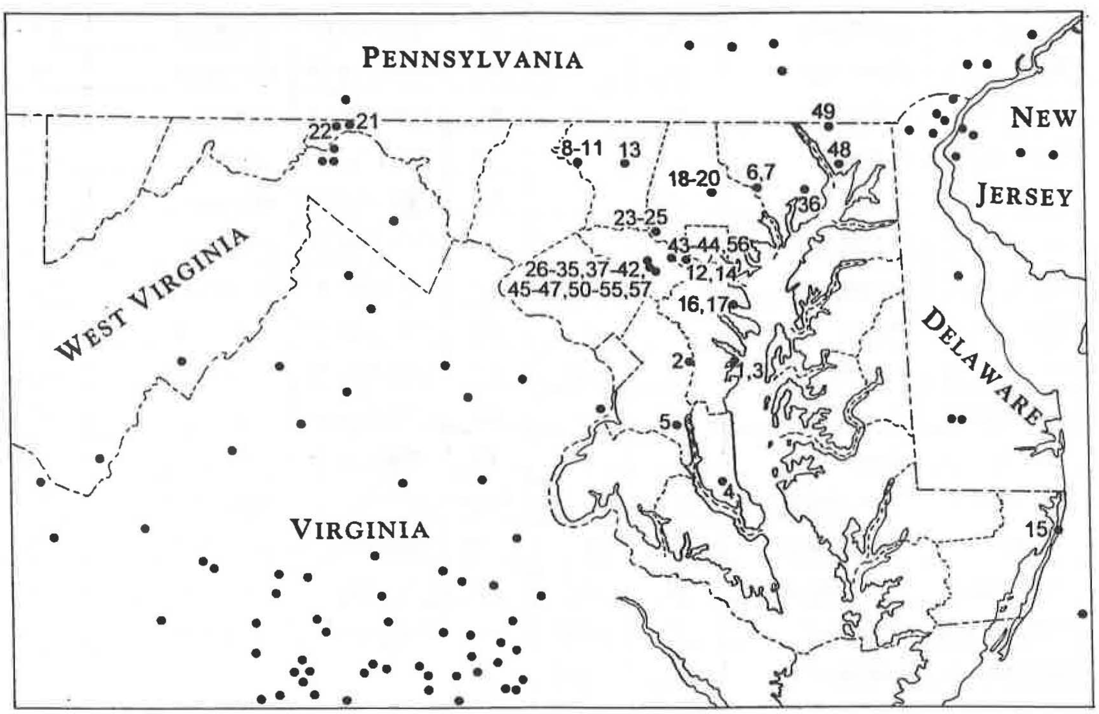

FIGURE 6.— Map showing approximate epicenters of historical earthquakes in and near Maryland, 1758-1998. (From data in Stover and others, 1984; National Earthquake Information Center, 1990, 1993; Delaware Geological Survey, Virginia Polytechnic Institute, and Lamont-Doherty Earth Observatory, written comm., 1993-1996; S. Baxter, written comm., 1998).

Earthquake swarms may be new to Maryland, but they have occurred in the Mid-Atlantic region on at least one previous occasion. A swarm of 11 very small, felt tremors occurred in Richmond, Virginia, during December, 1986 and January, 1987. There were several similarities with the Columbia swarm. Such a sequence was a first for Richmond. Magnitudes ranged from 1.5 to 2.2; hypocenters were quite shallow (less than 2.5 kilometers, or 1.5 miles), and the active fault was of a similar type and orientation to the fault identified in Columbia (Davison and Bodé, 1987).

TABLE 5.— Earthquakes in Maryland, 1758-1998. MMI is estimated maximum Modified Mercalli Intensity; M is magnitude, as determined by a variety of methods. (Data for 1758-1979 primarily from the Stover and others, 1981; 1990-1996 data from Delaware Geological Survey, Lamont-Doherty Earth Observatory, Virginia Polytechnic Institute, U.S. Geological Survey, and numerous firsthand accounts.)

No.	Date	Nearby Town	MMI	M	No.	Date	Nearby Town	MMI	M
1	1758 Apr 25	Annapolis	—	—	28	1993 Mar 10	Columbia	II-IV	2.5
2	1828 Feb 24	Bowie	—	—	29	1993 Mar 11	Columbia	I-II	2.0
3	1876 Jan 30	Annapolis	—	—	30	1993 Mar 14	Columbia	III-V	2.7
4	1876 Apr 10	Prince Frederick	III	—	31	1993 Mar 16	Columbia	I	<1.5
5	1877 Sep 01	Brandywine	III	—	32	1993 Mar 16	Columbia	I	1.8
6	1883 Mar 11	Fallston	IV	—	33	1993 Mar 17	Columbia	I	≤1
7	1883 Mar 12	Fallston	III	—	34	1993 Mar 19	Columbia	I	≈1
8	1902 Mar 10	Union Bridge	III	—	35	1993 Mar 19	Columbia	I	<1
9	1902 Mar 11	Union Bridge	III	—	36	1993 Mar 21	Abingdon-Bel Air	I-II	1-1.5
10	1903 Jan 01	Union Bridge	III	—	37	1993 Mar 22	Columbia	—	≈0
11	1903 Jan 01	Union Bridge	II	—	38	1993 Apr 04	Columbia	I-III	≈1.5
12	1906 Oct 13	Catonsville	III	—	39	1993 Apr 04	Columbia	I-III	≈1.5
13	1910 Jan 24	Westminster	II	—	40	1993 Apr 08	Columbia	III	≈1-1.5
14	1910 Apr 24	Catonsville	III	—	41	1993 Jul 09	Columbia	II-III	1.9
15	1928 Oct 15	Ocean City	IV	—	42	1993 Jul 12	Columbia	II-III	2.1
16	1930 Nov 01	Round Bay	III	—	43	1993 Oct 28	Ilchester	IV	2.1
17	1930 Nov 01	Round Bay		—	44	1993 Oct 28	Ilchester	III-IV	1.8
18	1939 Jun 22	Phoenix	III	—	45	1993 Nov 17	Columbia	II-III	≈1.5
19	1939 Nov 18	Phoenix	IV	—	46	1993 Nov 27	Columbia	I-II	<1.5
20	1939 Nov 26	Phoenix	V	≈3	47	1993 Nov 27	Columbia[1]	I-II	≈1.5
21	1962 Sep 07	Hancock	—	—	48	1996 Aug 07	Perryville	II	≈2.2
22	1978 Apr 26	Hancock	—	3.1	49	1996 Oct 17	Rising Sun	II-IV	2.2-2.5
23	1990 Jan 13	Randallstown	III-V	2.5-2.6	50-52	1996 Dec 06	Columbia[2]	I-II	<2
24	1990 Apr 04	Randallstown	II	1.6-1.7	53-55	1996 Dec 14	Columbia[3]	I-II	<2
25	1991 Sep 28	Randallstown	III	2.4	56	1996 Dec 16	Ilchester[4]	II	<2
26	1993 Mar 05	Columbia[1]	I	<1.5?	57	1996 Dec 22	Columbia	II-IV	2.3
27	1993 Mar 05	Columbia[1]	I	<1.5?					

1 Probable; based on quantity and quality of anecdotal accounts, but not confirmed by seismographs in the region. Magnitude estimated from other events in the series.
2 3 small tremors within a span of about 35 minutes.
3 3 small tremors within a span of about 75 minutes.
4 Small tremor about 12:10 a.m. EST, felt as much as 2.5 miles away)

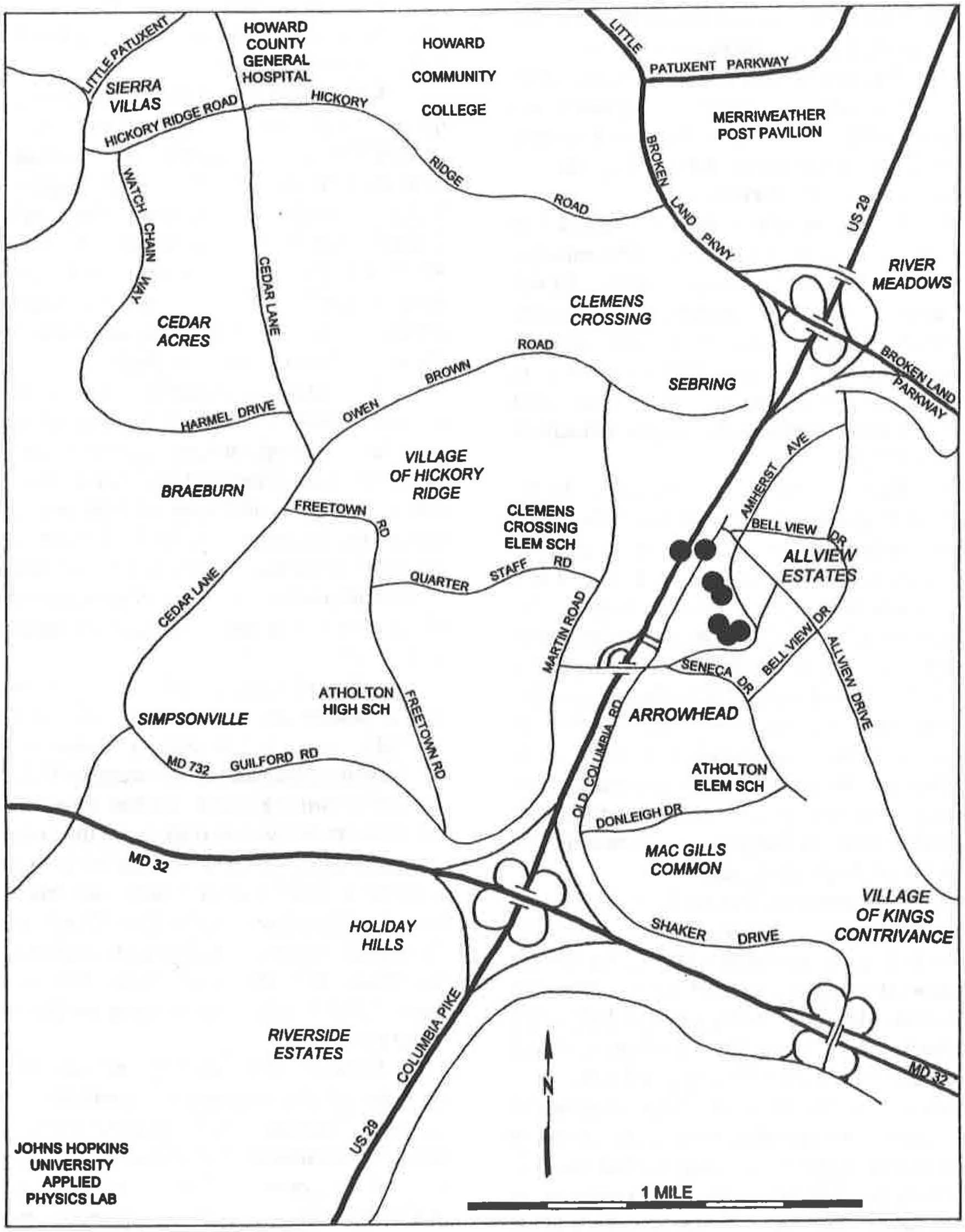

FIGURE 7.—Map of the Columbia, Maryland area showing approximate epicenters (●) of several of the very small tremors detected by the temporary array of seismometers in the area in 1993. No ground rupture or damage were found. Of the 25 confirmed and probable tremors in this area during 1993, 22 were centered near U.S. Route 29 just north of Maryland Route 32; three were centered near the community of Ilchester, a few miles to the north. (Source: Lamont-Doherty Earth Observatory, written communication, 1993)

ASSESSING SEISMIC HAZARD AND RISK

Earthquakes, large and small, are quite rare in stable continental interiors compared to those that occur along lithospheric plate boundaries. Yet, studies have found evidence that large earthquakes capable of producing surface ruptures do occasionally occur in stable continental interiors. The few documented cases most likely do not reflect the total of such occurrences.

Two were prehistoric, having occurred in southern Oklahoma about 1,200 to 3,000 years ago in an area that has low seismicity today. Seven events involving ground rupture in intraplate positions have occurred since 1986. Five were in Australia between 1968 and 1988; one was in Quebec's Ungava Peninsula in 1989; and the most recent was in south-central India in 1993 (Machette and Crone, 1993).

According to some seismologists, large, relatively infrequent earthquakes in stable continental interiors pose a serious but generally unrecognized threat in many parts of the world (Machette and Crone, 1993). Even moderate earthquakes can cause unusually widespread damage in these regions, in part because an earthquake's energy is transmitted very efficiently in the cold, thick crust that characterizes stable continental interiors. As a result, earthquakes in stable continental interiors propagate strong ground motion over larger areas than plate boundary earthquakes of equivalent size or magnitude, increasing the potential for widespread damage.

Recall that Maryland has not been the location of an earthquake having a magnitude ≥4.5 since 1568 (see p. 12), but also notice that the Baltimore-Washington area experienced intensity V from the New Madrid, Missouri, earthquakes of 1811-1812 and intensity IV-V from the Charleston, South Carolina, earthquake of 1886 (Appendix 2).

Because earthquakes in stable continental interiors occur infrequently, people are generally less prepared to cope with strong ground motion, and man-made structures are not designed to withstand severe shaking. Some seismic experts express concern that State and local officials in the eastern and central United States do not take earthquakes nearly as seriously as those in the West. People are generally less prepared to cope with strong ground motion, and man-made structures are not designed to withstand severe shaking (Machette and Crone, 1993). Few eastern states take earthquake stresses into account for their building codes (Grier, 1989).

Four terms need to be clearly defined and distinguished: seismicity, seismic hazard, seismic risk, and vulnerability.

Seismicity refers mainly to frequency of earthquake occurrence. For example, on average, central Virginia experiences more earthquakes per year than Maryland, so central Virginia has the higher seismicity. Seismicity also relates to the typical seismic energy release of earthquakes. Thus, a region having many small tremors may have a similar seismicity to one having a few moderate tremors. However, seismicity says little about the threat to life and property.

The term ***earthquake hazard***, or ***seismic hazard***, relates to so-called "primary effects," such as ground shaking, surface rupture, local uplift and subsidence, and liquefaction—effects that could be due to geologic conditions, as well as to the earthquake mechanisms. Seismic hazard is usually depicted in terms of maximum horizontal velocity or peak ground acceleration of seismic waves, both of which are indicators of probable ground motion, or shaking.

Although an earthquake of a given magnitude in the eastern and central U.S. will be felt more strongly and over a greater distance than the equivalent earthquake in the western U.S., there is variability among states, so that seismic hazard is not uniform across the region. In the latest Federal listing of states' seismic hazard (Table 6), Florida is rated as a "low" hazard, South Carolina is "high," and the remainder of the East Coast is rated as "medium" hazard. (This new ranking elevates Maryland and Delaware from low to medium hazard and South Carolina from moderate to high hazard.)

Seismic risk basically relates to possible damage and losses (economic and life) from earthquakes. Especially in "high risk" areas, state and local governments may decide what level of risk (i.e., the amount and type of loss) is acceptable. Building codes and zoning regulations will reflect that "acceptable loss." Seismic risk can be reduced if buildings are constructed to earthquake-resistant standards. That is already being done in places like California, and all new Federal buildings are required to incorporate appropriate earthquake resistant construction. ***Acceptable Risk*** has been defined in several ways, but one of the simpler and

more direct defines it as: "A specification of the acceptable number of fatalities due to the earthquake threat, or an equivalent statement in terms of buildings" (Hays, 1979). This translates into judgments by authorities, presumably at the state and local levels, for determining design requirements for engineered structures, or for taking certain social or economic actions (Gori, 1984). A level of "acceptability" has not yet been specifically quantified for the Mid-Atlantic region.

A comparison of the western and the eastern U.S. (i.e., west and east of the Rocky Mountains) may help show the differences and the relationships among these three terms. The western U.S. has a much greater ***seismicity*** than the eastern U.S., as shown by the fact that the western U.S. has many more earthquakes and those earthquakes tend to include larger events (i.e., more seismic energy). However, given the differences in geologic characteristics between the western and the eastern U.S., a magnitude 5 earthquake, for example, would likely be felt over a larger area and with more ground shaking in the eastern and central U.S. than in the western U.S.

When all known earthquakes are considered, the average rate at which damage has been produced by earthquakes during the historical period is similar east and west of the Rocky Mountains (Seeber, 1983). *If* the historical record of seismicity is representative of long-term activity, the overall level of earthquake ***hazard*** is similar in the eastern and western U.S. (Seeber, 1983; Seeber and Armbruster, 1988). However, historical seismicity may not be a reliable indication of future seismic events, especially in areas of historically low occurrence and low magnitudes.

In parts of the western U.S., high seismicity, history of destructive earthquakes, and high population density have led to adoption of earthquake-resistant measures in building codes and have even led to "retro-fitting" of some older (pre-code) structures. As a result, Southern California has many earthquake-resistant buildings. Maryland has very few earthquake-resistant buildings because its low seismicity has not warranted the financial investment. In terms of ***seismic risk***, a magnitude 5 earthquake in the eastern U.S. could be expected to do more damage (property loss) than a magnitude 5 in the western U.S., because (1) it will be felt over a broader area in the East and (2) there are fewer earthquake-resistant structures in the East. Remember, however, that the probability of a magnitude 5 earthquake is much greater in the western U.S. than in the eastern U.S.

TABLE 6.— General seismic hazard of the United States and its territories (FEMA, written and oral communication, 1998).

Low Hazard	Medium Hazard	High Hazard	Very High Hazard
Florida	Alabama	Arizona	Alaska
Iowa	Colorado	Arkansas	California
Kansas	Connecticut	Illinois	Hawaii
Louisiana	Delaware	Indiana	Idaho
Michigan	Georgia	Kentucky	Montana
Minnesota	Indiana	Missouri	Nevada
Nebraska	Maine	New Mexico	Oregon
North Dakota	MARYLAND	South Carolina	Puerto Rico and U.S. Virgin Islands
South Dakota	Massachusetts	Tennessee	Washington
Wisconsin	Mississippi	Utah	Wyoming
	New Hampshire		
	New Jersey		
	New York		
	North Carolina		
	Oklahoma		
	Pennsylvania		
	Rhode Island		
	Texas		
	Vermont		
	Virginia		
	West Virginia		

The earthquake hazard in the United States has been estimated in a variety of ways. Chief among them is the production of "risk maps." Such maps prove useful in establishing building codes, engineering design standards, and insurance rates. Risk maps are based either on earthquake history (relative risk) or on the probability of a certain magnitude earthquake.

Two examples of risk maps are shown in Figure 8. Figure 8a shows four zones of relative risk (0, 1, 2, 3 in order of increasing risk), based on the history of damaging earthquakes, evidence of strain release, and consideration of major geologic structures and provinces believed to be associated with earthquake activity.

This map has been widely used for several decades, and is still a familiar "risk map." However, it does not consider frequency of occurrence. Furthermore, there is no justification for assuming that events larger than those observed historically, especially in the East, will not occur in the future (McGuire, 1977).

It is also known that ground-motion attenuation ("dying out" of the shock waves with distance) is far less in the eastern U.S. than in the western states. Felt areas are, in general, one order of magnitude greater in the East than for similar earthquakes in the West (Bollinger, 1973; also see Table 7). In general, there is also greater uncertainty of ground-motion attenuation for eastern U.S. sites, because fewer strong-motion records are available to determine the eastern U.S. attenuation function. Nonetheless, according to this map, Maryland is appropriately placed into a zone of minor expected damage, corresponding to Modified Mercalli Intensity V to VI.

A more recent development considers the probability of earthquake occurrence. One example is illustrated in Figure 8b. Often referred to as a "seismic risk map," it would be more correct to call it a "seismic hazard map." Although probability is considered, this map is not really a probability map. Rather, it shows the expected level of ground shaking in terms of peak ground acceleration (as a percentage of g, the acceleration due to gravity) on rock sites for a 10 percent probability of being exceeded in 50 years. This is equivalent to a ***return period***, of 475 years.

According to Figure 8b, Maryland has a very low probability of experiencing a damaging earthquake in a 50-year period.

Moderate damage begins to occur at a peak ground acceleration of about 10-15 percent g—i.e., at magnitudes of about 5 to 6. Below 4 percent g, shaking effects are controlled by minor, non-damaging earthquakes. An acceleration as low as 0.1 percent g or more is perceptible to people (Algermissen and Perkins, 1976).

It is important to remember that these relationships are only rough estimates. Estimating maximum magnitudes is most limited where no active faults are known, where seismicity is low, and where near-maximum earthquakes may not have occurred in historical times. This applies to most of the eastern United States (Algermissen and Perkins, 1976), including Maryland.

Probabilistic maps (e.g., Fig. 8b) suggest that the chance of a *damaging* earthquake, let alone a *destructive* earthquake, affecting Maryland is very low. In the Mid-Atlantic region, a "damaging" earthquake might range from a magnitude 4.0 for very slight, localized, cosmetic damage to 5.0-5.5 for more widespread but still generally slight damage; a "destructive" earthquake would typically be on the order of a magnitude 6.0 or greater. "Damaging," as the term is used here, refers to cosmetic, non-structural damage to a building; it does not necessarily imply inexpensive to the individual homeowner. Examples include cracked plaster at magnitude 4 or a toppled chimney at magnitude 5. "Destructive" refers to cases in which there is significant structural damage to buildings and infrastructure (e.g., bridges, highways, railroads). Examples can include the collapse of a bearing wall (i.e., a weight-supporting wall) in a house or the shifting of a house on its foundation for a magnitude 6.0 to collapse of a bridge at 7.0. Keep in mind that these examples and magnitudes are generalizations; actual damages may vary. (Refer to the list of factors, p. 6-7.)

Many experts have talked about a high probability of "the big one" occurring in Southern California, but what about the eastern U.S.? The answer might surprise you.

On the basis of probability calculations, Robert L. Ketter, director of the National Center for Earthquake Engineering Research at the State University of New York at Buffalo, stated in 1988: "... the probability of a destructive earthquake occurring at a given, singular geographic site in the eastern part of the country within the next 15 to 25 years is relatively low. However, the probability of

one occurring *somewhere in the eastern United States* before the year 2000 can be considered better than 75 to 95 percent. Before the year 2010, nearly 100 percent." Although he declined to pinpoint a location and did not rule out the possibility of major events elsewhere, Dr. Ketter listed "obvious potential areas for consideration": the Charleston area, South Carolina; the Eastern Appalachian Range; the New York-Boston area; the Niagara-Buffalo-Attica, New York area; and the Ottawa and Charlevoix areas of Canada (Ketter, 1988).

Other seismologists, such as S. P. Nishenko of the U.S. Geological Survey, and Gilbert A. Bollinger of Virginia Polytechnic Institute and State University present a more conservative probabilistic scenario. Their analysis of earthquake records from 1727 to 1982 lead them to state that the probability of a damaging earthquake (magnitude ≥ 6.0) in the eastern U.S. by the year the year 2000 is fairly low (29 percent), by 2020 moderate to high (40 to 60 percent), and by 2090 nearly certain (97 percent) (Nishenko and Bollinger, 1990).

TABLE 7.— General relationship between Modified Mercalli Intensity (MMI) and earthquake magnitude for different regions of the United States (after Stover and Coffman, 1993).

Modified Mercalli Intensity	Magnitude			
	Eastern U.S.[1]	Western U.S.	Hawaii	Alaska
V	—	<5.0	<5.5	<6.0
VI	<5.0	5.0	5.5	6.0
VII	5.0	5.5	6.0	6.5
VIII	5.5	6.0	6.5	7.0
IX	6.0	6.5	7.0	7.5
X-XII	6.5	7.0	7.5	8.0

[1]Applies to the United States east of the Rocky Mountains—i.e., the eastern two-thirds of the U.S.

TABLE 8.— Approximate and general relationship among Magnitude, Modified Mercalli Intensity (MMI), and peak ground acceleration[1] (after Bolt, 1993).

Magnitude	Modified Mercalli Intensity	Average Peak Acceleration (% g)	Magnitude	Modified Mercalli Intensity	Average Peak Acceleration (% g)
...	III	<1.5	...	VIII	25-30
4.0	IV	1.5-2	7.0	IX	50-55
...	V	3-4	...	X	>60
5.0	VI	6-7	8.0	XI	--
6.0	VII	10-15	...	XII	--

[1]Peak accelerations are for firm ground, but vary greatly with intensity and with seismic source.

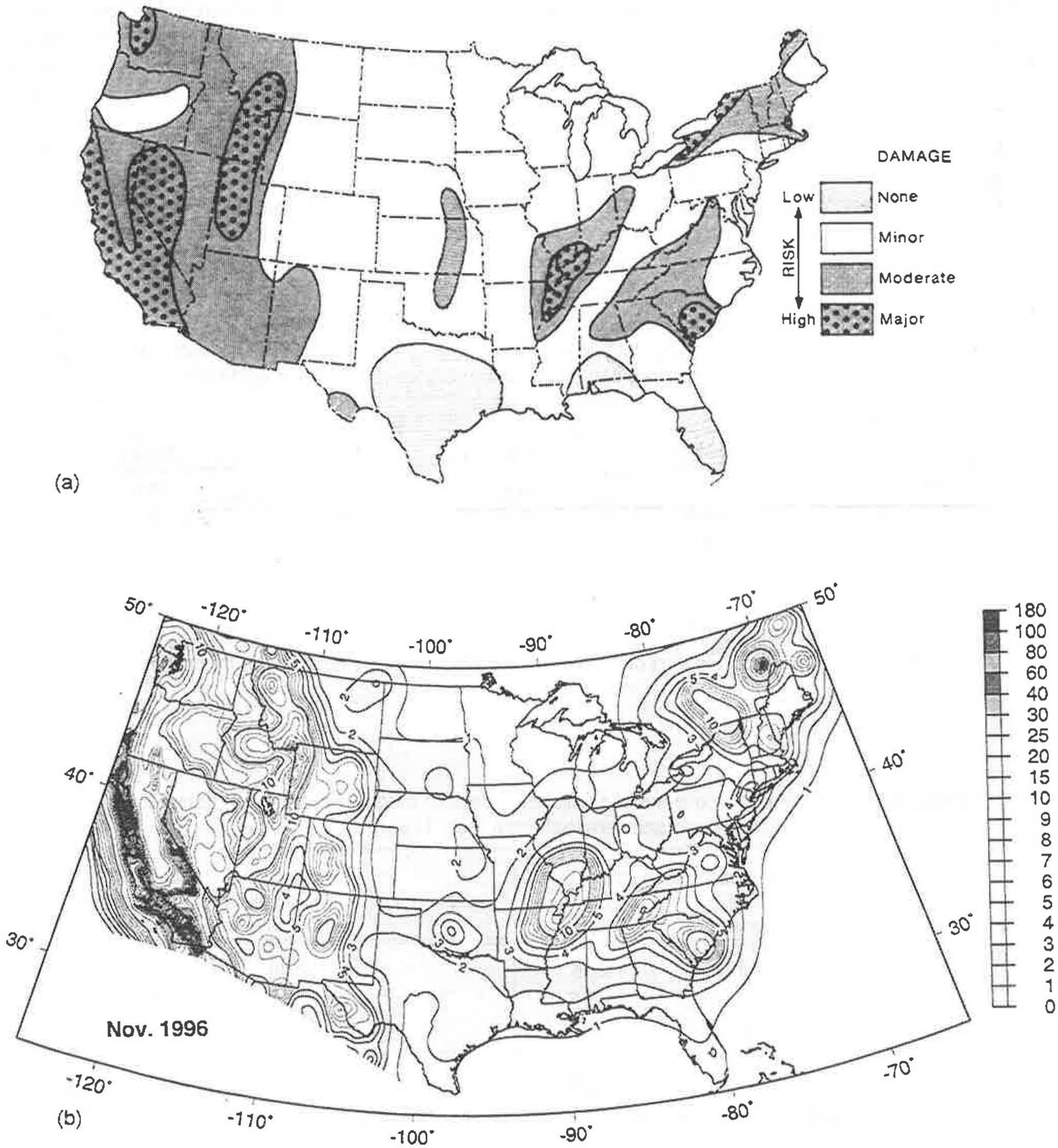

FIGURE 8.— Earthquake risk maps of the United States: **(a)** Relative risk map, or seismic zoning map, based to a large extent on known earthquake history (Algermissen, 1969). This map, with modifications, was incorporated in the 1979 edition of the BOCA Uniform Building Code. **(b)** Probabilistic map showing peak ground acceleration with a 10-percent probability of being exceeded (or 90-percent probability of not being exceeded) in 50 years (National Seismic Hazard Mapping Project, 1996, Internet site).

PREPARATION AND RESPONSE

In light of Maryland's low historical seismicity and the lack of an historical damaging earthquake, should citizens be concerned about a serious earthquake occurring in Maryland? Perhaps not, but some seismologists and earthquake engineers believe that citizens should not develop a false sense of security about earthquakes either. Again quoting Dr. Ketter: "Public awareness is the real problem at issue. I do not think that the average individual perceives that anything is going to happen within his or her lifetime because they haven't experienced it thus far" (Ketter, 1988).

Remote as they may seem, there are at least two possible hazards to consider, even from a relatively moderate earthquake (e.g., magnitude 5): fire and falling objects.

There are also three simple and very inexpensive precautions (mitigation measures) that could pay dividends if your home is near the epicenter of a magnitude 5 (or larger) earthquake. (1) Know the locations of the main shut-off valves for water and gas and the main electrical breaker box in your home; you may have to shut these off after an earthquake. (2) Hot water heaters can be strapped to a wall to prevent electric lines, gas lines, and water lines from being broken if the heater were to be shaken from its foundation. (3) There should be no mirrors, heavy paintings, or wall-mounted shelves above the head of a bed. That would prevent objects from falling onto people in bed if an earthquake occurred at night.

How to respond to an earthquake differs between Maryland and "earthquake country," like Alaska, Southern California, or Japan. In Southern California, for example, earthquakes capable of causing significant damage are common enough that some people take certain measures ahead of time in order to minimize problems later. Also, in "earthquake country," a large earthquake may last for 30 seconds or longer, giving people time to respond or react appropriately. A proper response depends on whether a person is indoors or outdoors. If indoors and if there is time to do so, the most common advice is "duck, cover, and hold." That means to get under the strongest cover possible, such as under a heavy table or in a doorway of a bearing wall. Then cover your face as protection from flying objects, including broken glass; and finally hold on to something to steady yourself during the shaking. Outdoors, move away from any road or street and away from anything that could fall on you, such as electric lines and walls; then lie down or sit down. If you are in a moving vehicle, pull off the road and stop as quickly as possible, but stay away from buildings or anything that might fall on you. As soon as the shaking stops, exit the car and go to a safe place.

In Maryland, the duration of earthquakes is generally so short (often a single "jolt" lasting one or two seconds) that there is simply no time to respond. By the time one realizes there has been an earthquake, it has passed. "Duck, cover, and hold" is often of little use in Maryland.

It is also important to do some things *after* an earthquake. Check your utilities, but do not turn them on, because the quake may have cracked water, gas, and electrical conduits. If you smell gas, open windows, shut off the main valve, call the gas company to report a possible gas leak, then leave the building. Likewise, if you see water lines are damaged, shut off the supply at the main valve; and if electrical wiring is shorting out, close the main breaker at the breaker panel. Stay out of severely damaged buildings; aftershocks may cause them to collapse.

Some other responses may seem obvious, but are often forgotten or overlooked at the time. For example, turn on your radio or television (if conditions permit) to get any emergency bulletins. Stay off the telephone except to report an emergency. Dial 911 only if you have damage to water, gas, or electric lines, if your house has possible structural damage, or if someone has sustained an injury. Do not dial 911 merely to report an earthquake or to find out if there has been an earthquake. Such misuse of 911 ties up the telephone lines, putting real emergencies in jeopardy.

For more information and suggestions concerning simple mitigation measures you can take at home, refer to the list of additional references on page 24, especially the booklets and brochures available from FEMA. The FEMA Internet site will also provide much similar information.

WHAT ABOUT INSURANCE?

During the Columbia earthquake swarm in 1993, many people asked about earthquake insurance for their homes. The Maryland Geological Survey does not make a recommendation for or against such insurance. However, the following might help someone decide for themselves.

In Maryland, insurance companies are required to make earthquake insurance available on request, usually as a rider on the homeowner's policy. Premiums can vary greatly from company to company. However, documenting pre-existing conditions of a house and a typically large deductible (e.g., possibly 10 percent of the value of the house) may dissuade some homeowners. Documentation of pre-existing conditions is very important because filing an insurance claim for the type of "cosmetic" damage that could be expected from a "typical" small tremor will require evidence that the damage was indeed caused by an earthquake and was not a pre-existing condition. "Structural" damage would be easier to document, but the probability of an earthquake occurring in Maryland of sufficient magnitude to cause structural damage is very small. The "typical" Maryland earthquake would not likely cause damage exceeding a 10-percent deductible.

A decision concerning earthquake insurance may have little to do with probabilities; it is often a personal choice for peace of mind. It is interesting to note that only 15-20 percent of eligible Californians carry earthquake insurance on their homes (Expert Review Committee, 1989).

For more information about earthquake insurance in Maryland, contact Consumer Affairs, Insurance Division, Department of Licensing & Regulation, 501 St. Paul Place, Baltimore, MD 21202.

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Internet Sites Referenced—http://

Federal Emergency Management Agency (FEMA) www.fema.gov

National Earthquake Hazards Program, Natural Resources Canada, www.seismo.emr.ca

National Earthquake Information Center (NEIC) U.S. Geological Survey, wwwneic.cr.usgs.gov

National Seismic Hazard Mapping Project, U.S. Geological Survey, geohazards.cr.usgs.gov/eq

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Annotated List of Selected Government Publications Concerning Earthquake Preparedness and Building Safety

(The following publications are free on request.)

Federal Emergency Management Agency
FEMA Distribution Center, Jessup, Md.
Call toll-free 1-800-480-2520

FEMA 46, *Earthquake Safety Checklist*. 1985. 9 p. Inexpensive, common-sense suggestions to make your home safer. Prepared in cooperation with the American Red Cross.

FEMA 48, *Coping with Children's Reactions to Earthquakes and Other Disasters*. 1986. This pamphlet was developed to help parents, teachers, and other adults deal with children's fears and anxieties following a quake.

FEMA 88, *Guidebook for Developing a School Earthquake Safety Program*. 1990. This 50-page book covers many topics, including planning, hazard identification, earthquake drills, and communication. It is designed to help school staff, parents, and students to develop an earthquake safety program for their schools.

FEMA 88a, *Earthquake Safety Activities for Children*. 1990. 37-page book contains excerpts from FEMA 159, *Earthquakes-A Teacher's Package for K-6*, developed by the National Science Teachers Assoc. with support from FEMA. Includes 16 sheets suitable for duplicating or making overhead transparencies.

FEMA 232, *The Home Builder's Guide for Earthquake Design*. 1992. This 57-page book will introduce you to many measures you can take during construction to make your house better able to withstand an earthquake.

FEMA L-143, *Preparedness in Apartments and Mobile Homes*. 1984. Directed toward those who "live with the threat of earthquakes every day," this 15-page brochure describes simple steps to limit the damage.

FEMA L-172, *Seismic Safety of Existing Buildings*. 1990. Probably of most interest to local governments and community leaders, this 8-page pamphlet describes other publications related to rehabilitation of existing buildings to make them better able to withstand earthquakes.

U.S. Geological Survey

USGS, 1986, *Safety and Survival in an Earthquake*. Pamphlet prepared in cooperation with the U.S. Dept. of Housing and Urban Development-FEMA. Available from USGS Book and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225.

USGS, *U.S. Geological Survey Teacher's Packet*. Request on school letterhead, indicate subject and grade level to: USGS, Geologic Inquiries Group, 907 National Center, Reston, VA 22092.

ADDITIONAL SITES ON THE INTERNET--http://....

California State University, Los Angeles: The *"Virtual Earthquake"* is an interactive site in which you learn by doing. Choosing from several geographic areas, you proceed step by step in the analysis of seismograms to determine the epicenter and Richter magnitude.
vflylab.calstatela.edu/edesktop/VirtApps/VirtualEarthQuake/VQuakeIntro.html

Federal Emergency Management Agency: Deals with earthquakes, floods, hurricanes, and more, with emphasis on preparedness and mitigation.
www.fema.gov
Click on SEARCH on the FEMA home page and type "earthquakes." Includes pages about mitigation and "earthquakes for kids."

National Geophysical Data Center: NGDC is part of the National Oceanic and Atmospheric Administration (NOAA). Information on earthquakes, magnetism, gravity, paleoclimate.
www.ngdc.noaa.gov

Seismological Society of America: A variety of information, but in particular *Seismology Resources for Teachers* contains lists of references, maps, slide sets, videotapes, computer hardware/software, seismographs, and databases.
www.geo.purdue.edu/seismology_resources.html

United States Geological Survey: The main home page of the USGS (http://www.usgs.gov) contains a wealth of geologic information. Several helpful USGS web sites are listed below.

- **Education Page:** The *USGS Learning Web*: More than earthquakes here, but check it out.
  www.usgs.gov/education/

- **Publications Page:** *This Dynamic Earth: The Story of Plate Tectonics*: An excellent publication. The entire text may be printed from the Internet site:
  pubs.usgs.gov/publications/text/dynamic.html
  Hard copy is available from: USGS Information Services, Box 25286, Building 810, Denver Federal Center, Denver, CO 80225. $6.00 (phone 1-800-USA MAPS).

  Another USGS Internet site is titled *Major Tectonic Plates of the World*. Includes map and very brief description of different types of plate boundaries.
  geology.er.usgs.gov/eastern/plates.html

- **Geological Hazards Team:** Information about earthquakes, volcanoes, landslides, and geomagnetism.
  gldage.cr.usgs.gov

- **National Earthquake Information Center:** This site offers a large variety of information on earthquakes worldwide. Includes near real-time listing of earthquakes. Various searchable catalogs of earthquake information and data.
  wwwneic.cr.usgs.gov
  This site also has a page on plate tectonics at:
  wwwneic.cr.usgs.gov/neis/plate_tectonics/rift_man.html

- **USGS Western Region:** The focus is on the western U.S., especially California.
  http://www-socal.wr.usgs
  This site includes two pages directed toward educational information:

  (1) *"Seismology at the Science Fair"* has suggestions for science fair projects, as well as links to subjects such as building a seismometer.
  quake.wr.usgs.gov/more/scifair/

  (2) *"Parent's Guide to Earthquakes"* is part of *Earthquake ABC*, a book written by second- and third-grade students in 1994 after the Northridge, California earthquake. The *Parent's Guide* was written by Dr. Lucy Jones, USGS-Pasadena, whose son was in the class.
  www-socal.wr.usgs/ABC/index.html
  Earthquake ABC includes *The Children's Book, The Parent's Guide* by Lucy Jones, and *Guide for Elementary School Teachers* by Paula Rao.
  The entire book can be viewed on-line from the publisher, Sirius Productions, at:
  http://home.earthlink.net/~torg/

University of Washington: *"Surfing the Internet for Earthquake Data"* consists of numerous links to original seismic data or seismic research information.
www.geophys.washington.edu/seismosurfing.html

APPENDIX 1. SIGNIFICANT EARTHQUAKES IN EASTERN NORTH AMERICA[1] — 1638-1996

List includes epicentral MMI≥VIII and/or felt area ≥100,000 mi^2. Magnitudes estimated for pre-1950 earthquakes. (Bolt, 1993; National Earthquake Hazards Program (Canadian) Internet site; Coffman and von Hake, 1973; Coffman, 1979; Lockridge, 1990; National Earthquake Information Center, monthly listings, 1989-1996; Stover and Coffman, 1993).

Date		Locality	Area (mi^2)	MMI	Magnitude	Comments
1638	Jun 11	Probably St. Lawrence Valley[2]	--	IX	--	Many stone chimneys toppled
1663	Feb 5	St. Lawrence River region	750,000	X	--	Chimneys broken in Massachusetts Bay area; unreliably documented
1732	Sep 16	St. Lawrence Valley	--	IX	--	7 killed in Montreal
1755	Nov 18	Cape Ann, Mass.	300,000	VIII	6.0	Many chimneys down, brick buildings damaged; felt from Nova Scotia to Chesapeake Bay
1828	Mar 9	Virginia (probably)	218,000	V	--	Minor damage
1852	Apr 29	Virginia (probably)	162,000	VI	--	Minor damage
1861	Aug 31	Virginia (probably)	300,000	VI	--	Minor damage
1869	Oct 17	Canada (felt south)	700,000	VIII-IX	--	--
1875	Dec 22	Arvonia, Va., Goochland Co.	50,000	VII	5.0	--
1884	Aug 10	near New York City	70,000	VI-VII	5.3	Felt from New Hampshire to Baltimore
1886	Aug 31	Charleston, S.C.	2,000,000	X	6.5-7	Damage $20 million; 60 killed
1897	May 31	Giles County, Va.	280,000	VII-VIII	5.8	Felt in 13 states
1905	Jan 27-28	Gadsden, Ala.	250,000	VII	--	--
1914	Feb 10	Eastern Canada	200,000	VII	--	Felt to the South in the U.S.
1916	Feb 21	Near Asheville, N.C.	200,000	VI	--	--
1916	Oct 18	Northeastern Alabama	100,000	VII	--	--
1925	Feb 28	St. Lawrence region	2,000,000	VIII	6.7-7.0	Felt to Virginia and to the Mississippi River; damage less than $100,000
1929	Aug 12	Attica, N.Y.	100,000	VIII	--	Chimneys fell
1929	Nov 18	Grand Banks of Newfoundland	80,000	X	7.2	Limited damage on land, but triggered large submarine landslide that ruptured 12 transatlantic cables, some breaks 150 miles apart; 27 killed by tsunami
1935	Nov 1	Timiskaming, Ontario		VIII	6.2	Felt as far west as Wisconsin and as far south as Charleston, W.Va. and Washington, D.C.
1944	Sep 4	Massena, N.Y.; Cornwall, Ont.	175,000	VIII	5.6	Damage $1.5 million; 2,000 chimneys damaged or destroyed in Cornwall
1980	Jul 27	NE Kentucky (near Maysville)	232,000		5.1	Damage $1 million
1989	Dec 25	Ungava Peninsula, Quebec	--	--	6.1-6.3	The first historical earthquake to produce surface rupture in the stable interior of N. America

[1] Maine, New Hampshire, Vermont, Massachusetts, Connecticut, Rhode Island, New York, Pennsylvania, New Jersey, Delaware, Maryland, Virginia, West Virginia, North Carolina, South Carolina, Kentucky, eastern Tennessee, Georgia, Alabama, Florida; Ontario, Quebec, Nova Scotia, New Brunswick, Newfoundland.

[2] According to Bolt (1993), the epicenter was near Plymouth, Massachusetts.

APPENDIX 2. THE THIRTY LARGEST EARTHQUAKES IN THE UNITED STATES — 1800-1997

(after Stover and Coffman, 1993; NEIC internet web site, 1998[1])

Rank	Magnitude[2]	Date	Location	Comments
1	9.2	Mar 28, 1964	Prince William Sound, Alaska	Quake killed 15, tsunami killed 125; $311 million property loss; felt area 700,000 mi^2; maximum MM intensity X
2	8.8	Mar 9, 1957	Andreanof Islands, Alaska	Destroyed two villages; $5 million damage
3	8.7	Feb 4, 1965	Rat Islands, Alaska	Sparsely populated; moderate damage; generated tsunami 35 feet high
4.5	8.3	Nov 10, 1938	East of Shumagin Islands, Alaska	Submarine earthquake; sparsely populated part of the Aleutian Islands
4.5	8.3	Jul 10, 1958	Lituya Bay, Alaska	Sparsely populated area; 5 killed
6	8.2	Sep 10, 1899	Yakutat Bay, Alaska	The largest of several in September, 1899; felt over a 250 mile radius; surface ruptures, avalanches; little damage; tsunami 34 feet high
7	8.15	Sep 4, 1899	near Cape Yakataga, Alaska	Sparsely populated; no casualties; felt 1,100 km (680 miles) away
8	8.0	May 7, 1986	Andreanof Islands, Alaska	Slight to moderate damage to some buildings on some of the islands
11	7.9	Feb 7, 1812	New Madrid, Missouri	Damage area 232,000 mi^2; felt area 2,000,000 mi^2
11	7.9	Jan 9, 1857	Fort Tejon, California	Rupture about 185 miles along San Andreas Fault; displacement as much as 30 feet; strong shaking lasted 1 to 3 minutes; buildings and large trees thrown down
11	7.9	Apr 3, 1868	Ka'u District, Island of Hawaii	77 deaths (tsunami 46; landslide 31); felt for over 350 miles
11	7.9	Oct 9, 1900	Kodiak Island, Alaska	Chimneys, windows, and a wharf destroyed
11	7.9	Nov 30, 1987	Gulf of Alaska	Damage moderate to light (broken glass-ware, cracks in plaster, etc.)
14.5	7.8	Mar 26, 1872	Owens Valley, California	At Lone Pine, 52 of 59 houses (mostly adobe or stone) destroyed; 27 killed; $250,000 damage
14.5	7.8	Feb 24, 1892	Imperial Valley, California (Calif.-Mexico border)	All adobe buildings destroyed in one town; fissures, rockslides
17	7.7	Dec 16, 1811	New Madrid, Missouri	Two very similar quakes only 6 hours apart; MM intensity V in Baltimore-Washington area
17	7.7	Apr 18, 1906	San Francisco, California	Quake and resulting fires caused an estimated 3,000 deaths and $524 million property damage (700 and $20 million from the quake alone); total rupture on San Andreas Fault was about 270 mi.; lateral displacement about 21 ft.
17	7.7	Oct 3, 1915	Pleasant Valley, Nevada	Epicentral region nearly uninhabited; adobe buildings damaged or destroyed; mines collapsed; increased flow in springs and streams in northern Nevada

(continued on next page)

THE THIRTY LARGEST EARTHQUAKES IN THE UNITED STATES (continued)

Rank	Magnitude	Date	Location	Comments
19	7.6	Jan 23, 1812	New Madrid, Missouri	
20	7.5	Jul 21, 1952	Kern County, California	12 killed; $60 million in damage
22.5	7.3	Nov 4, 1927	west of Lompoc, California	Fairly moderate damage: toppled chimneys, shifted foundations
22.5	7.3	Dec 16, 1954	Dixie Valley, Nevada	Sparsely populated, relatively minor damage
22.5	7.3	Aug 18, 1959	Hebgen Lake, Montana	28 killed, mostly campers by landslides; $11 million damage; created Quake Lake on Madison River
22.5	7.3	Oct 28, 1983	Borah Peak, Idaho	2 killed; $12.5 million damage; maximum MM intensity IX
25	7.2	Nov 8, 1980	off the coast of Humboldt, County, California	6 injuries; $2 million damage mostly due to US 101 overpass collapse onto railroad
26.5	7.1	Apr 13, 1949	Olympia, Washington	Heavy damage in Washington and Oregon; killed eight people and injured many others; felt to western Montana and southern Oregon
26.5	7.1	Oct 17, 1989	Loma Prieta, California	Occurred during a World Series game; epicenter in a mountainous area south of San Francisco; caused an estimated $4-6 billion in damage; many of the 66 deaths resulted from a double-decker freeway collapsing on cars
29	6.7	Aug 31, 1886	Charleston, South Carolina	$20 million in damage; destroyed or damaged most buildings in Charleston; 60 killed; MM intensity X; felt area 2,000,000 mi^2. Felt in New York; Boston; Milwaukee; Havana, Cuba; and Ontario, Canada; intensity IV-V in Baltimore-Washington area
29	6.7	May 2, 1983	Coalinga, California	Maximum MM intensity VII; injured 45; caused $31 million in damage; felt from Los Angeles to Sacramento and from San Francisco to Reno, Nevada
29	6.7	Jan 17, 1994	North Ridge, California	$13-20 billion in damage; 57 killed

[1] wwwneic.cr.usgs.gov/neis/eqlists

[2] Magnitudes listed are "moment magnitudes," Mw, which are usually several tenths higher than most other measures of magnitude.

APPENDIX 3. RECORD WORLD EARTHQUAKES

A. THE TEN LARGEST EARTHQUAKES IN THE WORLD, 1900-1997. (NEIC web site, 1998)[1]

Rank	Magnitude[2]	Date	Location	Rank	Magnitude[2]	Date	Location
1	9.5	May 22, 1960	Chile	6.5	8.7	Nov 06, 1958	Japan
2	9.2	Mar 28, 1964	Alaska	6.5	8.7	Feb 04, 1965	Alaska
3	9.1	Mar 09, 1957	Alaska	8	8.6	Aug 15, 1950	India
4	9.0	Nov 04, 1952	Russia	9.5	8.5	Nov 11, 1922	Argentina
5	8.8	Jan 31, 1906	Ecuador	9.5	8.5	Feb 01, 1938	Indonesia

[1] wwwneic.cr.usgs.gov/neis/eqlists
[2] Magnitudes listed are moment magnitudes, Mw, which are usually several tenths higher than most other measures of magnitude.

B. THE TWENTY DEADLIEST EARTHQUAKES ON RECORD — Listed in order of number of deaths. (NEIC web site, 1998)[1]

Rank	Magnitude	Date	Location	Deaths	Comments
1	—	Jan 23, 1556	Shansi, China	830,000	
2	8.0	Jul 27, 1976	Tangshan, China	255,000 [2]	
3	—	Aug 9, 1138	Aleppo, Syria	230,000	
4	8.3	May 22, 1927	near Xining, China	200,000	Large fractures
5	—	Dec 22, 856[3]	Damghan, Iran	200,000	
6	8.6	Dec 16, 1920	Gansu, China	200,000	Major fractures, landslides
7	—	Mar 23, 893[3]	Ardabil, Iran	150,000	
8	8.3	Sep 1, 1923	Kwanto, Japan	143,000	Great Tokyo fire
9	7.5	Dec 28, 1908	Messina, Italy	70,000-100,000	Deaths from earthquake and tsunami
10	—	Sep, 1290	Chihli, China	100,000	
11	—	Nov, 1667	Shemakha, Caucasia	80,000	
12	—	Nov 18, 1727	Tabriz, Iran	77,000	
13	8.7	Nov 1, 1755	Lisbon, Portugal	70,000	Great tsunami
14	7.6	Dec 25, 1932	Gansu, China	70,000	
15	7.8	May 31, 1970	Peru	66,000	Great rock slide
16	—	1268	Silicia, Asia Minor	60,000	
17	—	Jan 11, 1693	Sicily, Italy	60,000	
18	7.5	May 30, 1935	Quetta, Pakistan	30,000-60,000	Quetta almost completely destroyed
19	—	Feb 4, 1783	Calabria, Italy	50,000	
20	7.7	Jun 20, 1990	Iran	50,000	Landslides

[1] wwwneic.cr.usgs.gov/neis/eqlists
[2] Official casualty figure; estimated death toll as high as 655,000.
[3] These dates are prior to 1000 A.D. No digit is missing.

APPENDIX 4.

EARTHQUAKE REPORTING FORM

(adapted from the U.S. Geological Survey report form OMB No. 42-R1700)
Feel free to photocopy this form for your use in the event of an earthquake.
Mail it or fax it to:

MARYLAND GEOLOGICAL SURVEY
Environmental Geology Program
2300 St. Paul Street
Baltimore, MD 21218-5210
Phone 410-554-5500 — Fax 410-554-5502

Please answer this questionnaire and return to the address above as soon as possible.

1. Name of person filling out form ____________________
   Address ____________________
   City ____________________ County ____________________
   State ____________________ Zip code ____________________
   If you felt the earthquake, complete the personal report; If others felt the earthquake but you did not, skip the personal report and complete the community report.

PERSONAL REPORT

2. Did you personally feel the earthquake? ☐ Yes ☐ No
   If you have ever felt an earthquake before, where and when? ____________________
   Were you awakened by the earthquake? ☐ Yes ☐ No
   Were you frightened by the earthquake? ☐ Yes ☐ No
   Date earthquake occurred: ____________________
   Time earthquake occurred: __________ ☐ AM ☐ PM ☐ Standard time ☐ Daylight savings time
   Were you at ☐ Home ☐ Work ☐ Other ____________________
   Town and zip code of your location at time of earthquake ____________________
   Nearest street and cross street (or numbered highways) at your location at time of earthquake:
   ____
   Check your activity when the earthquake occurred:
   ☐ Walking ☐ Sleeping ☐ Lying down ☐ Standing
   ☐ Driving (car in motion) ☐ Sitting ☐ Other ____________________
   ☐ Inside ☐ Outside
   If you were inside, on what floor were you? ____________________
   Did you have difficulty in standing or walking? ☐ yes ☐ no
   Vibration could be described as ☐ Light ☐ Moderate ☐ Strong
   Was there earth noise? ☐ No ☐ Faint ☐ Moderate ☐ Loud
   Direction of noise ☐ North ☐ South ☐ East ☐ West
   Estimated duration of shaking ☐ Sudden, sharp (less than 10 seconds) ☐ Long (30-60 secs)

COMMUNITY REPORT

Town and zip code ____________________
DO NOT INCLUDE EFFECTS FROM OTHER COMMUNITIES/TOWNS.
Check one box for each question that is applicable.

3. (a) The earthquake was felt by ☐ No one ☐ Few ☐ Several ☐Many ☐ All?
   (b) This earthquake awakened ☐ No one ☐ Few ☐ Several ☐Many ☐ All?
   (c) This earthquake frightened ☐ No one ☐ Few ☐ Several ☐Many ☐ All?

(continued on other side)

4. What indoor physical effects were noted in your community?

Windows, doors, dishes rattled	☐ Slightly	☐ Loudly	
Walls creaked	☐ Slightly	☐ Loudly	
Building trembled (shook)	☐ Slightly	☐ Moderately	☐ Strongly
Hanging pictures (more than one)	☐ Swung	☐ Out of place	☐ Fell
Windows	☐ Few cracked	☐ Some broken	☐ Many broken
Small objects overturned	☐ Few	☐ Many	
Small objects fallen	☐ Few	☐ Many	
Items thrown from shelves	☐ Few	☐ Many	
Glassware/dishes broken	☐ Few	☐ Many	
Light furniture or small appliances	☐ Overturned	☐ Damaged seriously	
Heavy furniture or appliances	☐ Overturned	☐ Damaged seriously	
Did hanging objects or doors swing?	☐ Slightly	☐ Moderately	☐ Violently
Can you estimate direction?	☐ North/South	☐ East/West	☐ Other__________

5. Indicate effects of the following types to interior walls if any:

Plaster/stucco	☐ Hairline cracks	☐ Large cracks (many)	☐ Fell in large amounts
Dry wall	☐ Hairline cracks	☐ Large cracks (many)	☐ Fell in large amounts

6. What outdoor physical effects were noted in your community?

Trees and bushes shaken	☐ Slightly	☐ Moderately	☐ Strongly
Standing vehicles rocked	☐ Slightly	☐ Moderately	
Moving vehicles rocked	☐ Slightly	☐ Moderately	
Water splashed onto sides of ponds, swimming pools	☐ Yes	☐ No	
Chimneys	☐ Cracked	☐ Twisted	☐ Fallen
Stone or brick fences/walls	☐ Open cracks	☐ Fallen	☐ Destroyed
Sidewalks	☐ Large cracks	☐ Large displacements	
Streets or highways	☐ Large cracks	☐ Large displacements	

7a. Check below any structural damage to buildings:

Foundation	☐ Cracked		☐ Destroyed
Interior walls	☐ Split	☐ Fallen	☐ Separated from ceiling or floor
Exterior walls	☐ Large cracks	☐ Bulged outward	
	☐ Partial collapse		☐ Total collapse

7b. What type of construction was the building that showed this damage?

☐ Wood ☐ Stone ☐ Cinder block ☐ Brick ☐ Brick veneer

☐ Reinforced concrete ☐ Mobile home ☐ Other ______________________

7c. What was the type of ground under the building?

☐ Don't know ☐ Sandy soil ☐ Marshy ☐ Artificial fill

☐ Hard rock ☐ Clay soil ☐ Sandstone, limestone, shale

7d. Was the ground: ☐ Level ☐ Sloping ☐ Steep?

7e. Can you estimate the age of the building?

☐ more than 50 years ☐ 25-50 years ☐ 10-25 years ☐ less than 10 years

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Thank you for your time and information. Please mail this report to Maryland Geological Survey, Environmental Geology Program, 2300 St. Paul Street, Baltimore, MD 21218-5210; or fax it to 410-554-5502.

GLOSSARY

acceleration: Acceleration is the rate of increase in velocity—i.e., how much the velocity increases in a unit of time. It thus has units of velocity per unit time (e.g., feet/sec/sec). When an object accelerates, the object experiences the acceleration as a force. For example, we have all experienced a force associated with acceleration when we are pushed back into the car seat as a car accelerates quickly. Acceleration is often expressed in terms of the acceleration of a falling object due to gravity, g.

During an earthquake, "particles" in the earth's crust also accelerate with the passage of shock waves, so engineers describe ground shaking in terms of acceleration. One of the most common is *peak ground acceleration*. [Also see *percent g* and *peak ground acceleration*.]

acceptable risk: a probability of occurrences of social or economic consequences due to earthquakes that is sufficiently low (e.g., in comparison to other natural or manmade risks) as to be judged by authorities to represent a realistic basis for determining design requirements for engineered structures, or for taking certain social or economic actions (Gori, 1984).

aftershock(s): in general, one or more smaller earthquakes that occur after a larger earthquake and related in time and space to that larger earthquake. [Contrast to *foreshock*.]

amplitude (of a seismic wave): the amount the ground moves as the wave passes by. (An illustration, the amplitude of an ocean wave is one-half the distance between the crest and the trough of the wave. The amplitude of a seismic wave can be measured from the signal recorded by a *seismograph*.)

asthenosphere: the relatively soft, plastic layer of the earth's upper *mantle* that is characterized by low seismic wave velocities; lies directly below the *lithosphere*; may be partially melted. It begins about 100 km (62 miles) below the earth's surface and extends to a depth of about 350 to 500 km (220 to 310 miles).

attenuation: the reduction in *amplitude* of a *seismic wave* with time and/or distance traveled. Attenuation rates vary with geologic conditions.

body wave(s): one of the general types of *seismic waves* distinguished by their ability to travel through the body of the earth. [Also see *P wave* and *S wave*. Contrast with *surface wave*.]

core (of the earth): the central, spherical part of the earth beginning at a depth of about 2,900 km (1,800 miles) and having a radius of 3,477 km (2,160 miles). It is thought to be made up mainly of iron and nickel; consists of a solid inner and a liquid outer core.

crust (of the earth): the relatively rigid outermost layer of the earth that lies immediately above the *mantle*. Thickness ranges from 25 to 60 km (15 to 40 miles) under continents and from 4 to 6 km (2.5 to 5.5 miles) under deep oceans.

earthquake: a vibration of the earth caused by the sudden release of stored *strain* energy as rocks inside the earth fracture and move along a *fault*.

elastic: the property whereby an ideal material that is deformed under some force rebounds to its original shape and size after the stress is removed.

elastic rebound theory: a theory about the general origin and mechanism of earthquakes. It says that rocks in the earth's crust undergo elastic deformation, or *strain*, due to build-up of stresses. By the breaking of the rock in the crust or by movement along a *fault*, the energy that had been stored during deformation is released suddenly in the form of an earthquake and such a movement returns the rocks to a condition of little or no strain.

epicenter: the point on the earth's surface directly above the *focus*, or *hypocenter*; it is generally the site where seismic waves first arrive. [Also see *focus* and *hypocenter*.]

fault: a fracture or fracture zone along which there has been displacement (slipping) of the sides relative to each other parallel to plane of movement.

focus: the point within the earth where an earthquake originates; the initial rupture point of an earthquake, where the strain energy is first converted to elastic wave energy; also called *hypocenter*.

foreshock: in general, one or more earthquakes that occur before a larger earthquake and related

in time, space, and mechanism to that larger earthquake. [Contrast to *aftershock*.]

hazard: See **seismic hazard**.

hypocenter: the calculated position of the *focus* of an earthquake; usually used interchangeably for *focus*. [See *focus*.]

intensity: a descriptive measure of the severity of an earthquake based on visual observation and felt reports. [Also see *Modified Mercalli Intensity Scale*.]

intraplate: within the interior of a *lithospheric plate*, in contrast to being at a plate boundary. (For example, Maryland lies in an intraplate position within the North American plate.)

liquefaction: a process in which certain types of water-saturated sediments behave as a liquid rather than as a solid when shaken during an earthquake.

lithosphere: collectively the earth's crust and upper mantle; it lies above the *asthenosphere*; it contains the continents and ocean floors.

lithospheric plates: large, relatively rigid sections that make up the *lithosphere* and move slowly with respect to each other (i.e., moving apart, or colliding, or slipping past each other.

magnitude (of an earthquake): an objective (numerical) measure of earthquake size, closely related to the amount of seismic energy released. There are several different, but roughly comparable, measures of earthquake magnitude. In general, an increase of one magnitude unit corresponds to 10 times greater ground motion, but 31 times the seismic energy. [Also see *Richter scale*.]

mantle (of the earth): the layer of the earth below the crust and above the core; it is divided into the upper mantle and lower mantle with a transition zone between. It begins at a depth of about 40 to 100 km (25 to 62 miles) and extends to about 2,900 km (1,800 miles).

mitigation: the process of making something (e.g., earthquake damage and losses) milder or less severe. Mitigation includes any activities that prevent an emergency, reduce the chance of an emergency happening, or lessen the damaging effects of unavoidable emergencies. Earthquake mitigation is at the heart of the Earthquake Hazards Reduction Act of 1977 (amended in 1990), which established the National Earthquake Hazard Reduction Program (NEHRP).

Modified Mercalli Intensity Scale: a 12-point scale that describes the effects of an earthquake. Lower intensities describe increasing degrees of people's reactions; higher intensities describe increasing degrees of damage and other physical effects.

moment magnitude: a magnitude calculated from an earthquake's *moment*, a quantity proportional to the rigidity of the rock times the slip on the fault times the area of the fault surface that slips; it is related to the total energy released in the earthquake. Unlike other measures of magnitude, moment magnitude can be determined from seismograms and also from field measurements, which allows us to measure the size of old earthquakes and compare them to instrumentally recorded events. Moment magnitude provides an estimate of earthquake size that is valid over the complete range of magnitudes, a characteristic that was lacking in other types of magnitude.

peak ground acceleration (PGA): One of several quantitative ways to describe the level of ground shaking is the maximum, or peak, value of horizontal ground acceleration at a site due to the seismic waves from an earthquake. PGA is usually expressed as a percentage of g, the acceleration of a falling object due to gravity. PGA is a good index to hazard for short buildings, up to about 7 stories. (Adapted from the Internet http://geohazards.cr.usgs.gov/ eq/faq).

P wave(s): the faster moving of two body waves, hence the name "primary wave." It moves through the earth with a "compressional-dilatational" (or "push-pull, back-and-forth") motion of rock materials in the same direction as the path of the P wave. [Contrast with *S wave* and *surface wave*.]

plate tectonics: the theory that the lithosphere is divided into about ten or twelve major plates, each roughly 100 km (60 miles) thick, that move relative to one another, causing seismic and tectonic activity along their boundaries.

primary effects: earthquake effects directly attributable to the earthquake itself — e.g., damage or destruction caused directly by ground shaking, ground rupture, surface faulting, local uplift and subsidence, and ground liquefaction. [Contrast with *secondary effects*.]

primary wave: See **P wave**.

return period: *Return period*, or more properly the average return period, of an earthquake is the number of years between occurrences of an earthquake of a given magnitude at a particular site. *Return period* is best described in terms of probabilities. For example, for an earthquake having a 100-year average return period, there is about an 18 percent chance that it will occur in the next 20 years, a 39 percent chance that it will occur in the next 50 years, or a 63 percent chance that it will occur in the next 100 years.

Richter Scale: the standard measurement scale for earthquake magnitude, developed in 1935 by California seismologist Charles Richter. The scale is logarithmic, meaning that an increase of one magnitude represents a tenfold amplification of the ground motion. In theory, there is no upper limit, but the strength of earth materials limits magnitude for all intents and purposes to approximately 9. Very small earthquakes can have negative magnitudes.

risk: See **seismic risk**.

S wave(s): the slower moving of two body waves, hence the name "secondary wave." It moves through the earth with a "shear," or "shaking" motion of rock materials perpendicular to the path of the S wave. S waves cannot travel through liquids. [Contrast with *P wave* and *surface wave*.]

secondary effects: damage due to other than the direct (primary) impact on the ground, such as damage from fires (caused by broken gas and electric lines), landslides, and seismic sea waves (tsunamis). [Contrast with *primary effects*.]

secondary wave: See **S-wave**.

seismic hazard: a term relating to *primary effects*, especially ground shaking—effects that could be due to geologic conditions, as well as to the general nature of the earthquake mechanisms. Seismic hazard is usually depicted in terms of some quantitative measure of ground shaking, such as maximum horizontal velocity or acceleration of seismic waves. [Contrast with *seismic risk* and *seismicity*.]

seismic risk: (1) an assessment or determination of possible damage and losses (economic and life) from earthquakes, and thus is related to population density and the type and density of buildings. (2) *Relative risk* is a comparative assessment of one site to another; *probabilistic risk* is the odds of earthquake occurrence within a given time interval and region. [Contrast with *seismic hazard* and *seismicity*. Also see *acceptable risk*.]

seismic wave(s): a vibrational disturbance in the earth that travels at speeds of several kilometers per second. The main types are *body waves*, consisting of P (fastest), and S (slower) waves, and *surface waves* (slowest). They are produced by earthquakes.

seismicity: a general term relating mainly to the frequency of earthquake occurrence for a particular site or region, but also to the typical seismic energy release of earthquakes. [Contrast with *seismic hazard* and *seismic risk*.]

seismogram: the record of seismic waves as recorded by a *seismograph*.

seismograph: a device that records seismic waves. [Also see *seismometer* and *seismogram*.]

seismometer: an instrument, typically buried in the ground or encased in bedrock, that detects *seismic waves* and transmits them to a recorder, known as a *seismograph*.

stable continental interior: an area within a continent that is marked by low levels of seismic and/or tectonic activity; typically occupies an *intraplate* position.

strain: deformation; strictly speaking, a change in size and shape of some material as a result of an external force or stress.

strain energy: potential energy stored in rock under pressure that, when released suddenly, produces an earthquake.

surface wave(s): a type of seismic wave that originates at and travels only along the surface of the earth, being generated mainly by interactions of body waves at the earth's surface; surface-wave velocities are less than those of P waves and S waves. The two main types of surface waves are Love waves and Rayleigh waves, each with their own characteristics.

swarm: multiple earthquakes occurring in nearly the same location over a relatively short period of time (e.g., weeks to months), with no single earthquake standing out as the major event in the series. A swarm does not have the pattern associated with *aftershocks* and *foreshocks*.

tremor: a general name for a relatively small earthquake; sometimes used with reference mainly to *aftershocks* and *foreshocks*.

tsunami: Often incorrectly called "tidal waves," tsunami are large, very fast-moving sea waves that are typically caused by submarine earthquakes, submarine landslides, or volcanic eruptions. Speeds can exceed 800 or 900 km/hr (500-550 mph or more). They pose little or no danger in deep water or the open ocean, but in shallow coastal waters, the water wave "piles up" to heights of 30 meters (100 feet) and can be very destructive and deadly. The name comes from the Japanese word for "harbor wave."

INDEX

ERRATA

Earthquakes in Maryland
Maryland Geological Survey Educational Series No. 9
By James P. Reger
1999

Page 14, Table 5: For Event #16, the Modified Mercalli Intensity (MMI) should be IV, not III.

Note: For an updated list of earthquakes, request a free copy of Fact Sheet 13 from the Maryland Geological Survey's Publications Office (phone 410-554-5500; e-mail publications@dnr.state.md.us) or go to the Maryland Geological Survey web site at http://www.mgs.md.gov/esic/fs/fs13.html.

Page 17, Table 6. In the "Medium Hazard" column, delete Indiana and add Ohio.

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