Readings and Notes An Introduction to Earth Science

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Earthquakes

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EARTHQUAKES

For centuries, earth scientists have known where the major earthquakes occurred. They also knew they occurred in the same locales as the most violent volcanoes, a fact that led to centuries of arguments as to which was the cause of the other. Now we know that they are not cause and effect; they are both associated with the convergent plate margins. During the mid-1900s, another major zone of both volcanic and earthquake activity was discovered, namely the divergent margins, the most important site being the oceanic ridges. Since then, we have also come to understand the occurrence of volcanic activity within the plates as being located over hot spots beneath the plates. All of this new knowledge has been the result of the theory of plate tectonic. In our discussions of volcanism, we learned that the observed difference in volcanic activity between convergent and divergent plates is due to the type of magma involved. We must now explain why the earthquakes associated with convergent plate margins are of much higher magnitude than those associated with divergent plate margins. For this we must review our discussion of stress and strain.

EARTHQUAKE MAGNITUDE.

The magnitude of an earthquake refers to the actual amount of Earth movement and energy released during faulting. In our discussion of rock deformation, we learned that when stress is applied to rocks, energy is stored during the initial elastic phase of deformation up to the elastic limit after which the rock must respond by either plastic deformation during which the stored energy is consumed as the rocks are folded or by brittle deformation during which the rock breaks to form a fault with the stored energy being released as a shock wave.

The amount of energy stored before reaching the elastic limit is determined by the inherent strength of the rock. Rocks are very strong under compression, meaning that the amount of energy stored during the elastic phase of deformation and released during brittle failure will be potentially large. Conversely, rocks are inherently weak under tension meaning that significantly less energy is stored during the elastic phase of deformation and released during the brittle failure. A bit of historical trivia to illustrate this difference is a comparison of the architecture of ancient Greece and of Rome. The many columns that characterized ancient Greek architecture were necessitated because of the inability of the Greeks to overcome the inherent weakness of rocks under tension. The Greeks spanned the distance between columns with flat rocks called lintels. Although each lintel was being subjected to rotational compression, the forces that developed within the lintel were tensional. Because rock is weak under tension, the lintels would sag under their own weight and eventually fail if the distance spanned was too far. The Romans, on the other hand, spanned between columns with one of their very few true inventions, the arch. The secret of the Roman arch was the keystone. Because the keystone acted as a wedge, the contact between the keystone and the adjacent component of the arch was under non-rotational compression. This force was transferred by non-rotational compression to subsequent components of the arch, to the columns, and to the ground. In summary, the entire structure was subjected to non-rotational compression, the situation under which rock is strongest. As a result, we can thank the Romans for all of the vaulted ceilings and domes in buildings throughout the world. In terms of the relative amount of energy released during earthquakes, earthquakes associated with convergent plate margins are potentially of high magnitude because the rocks are under compression and store significant amounts of energy before the elastic limit is reached and movement is initiated along the largest reverse faults on Earth, namely, the zones of subduction..

Conversely, earthquakes associated with divergent margins are always of low magnitude because rocks are the weakest under tension and undergo normal faulting before significant amounts of energy can be stored.

SEISMIC SHOCK WAVES: The energy released during faulting is in the form of shock waves referred to specifically as seismic waves. In general, shock waves are of two types: 1) shear waves and 2) compression waves. Shear waves can only be transmitted through solids because only solids can be "sheared". As shear waves are propagated through a solid material, the individual components of the solid are being moved *perpendicular* to the direction of propagation. The propagation of shear waves is best illustrated as a sine wave with a particular amplitude and wavelength.

Compression waves can propagate through solids, liquids or gases. As compression waves propagate through any medium, the material is moved back and forth in the direction of propagation. Perhaps the best model to illustrate a compression wave is a the toy spring called a "Slinky". n example of a compressive wave is sound. As the compression wave arrive at our ears, the ear drum is moved in and out, transferring the energy to the inner ear where it is transferred via the cochlea to the brain where it is interpret it as a sound.

FOCUS and EPICENTER: Focus is the point at which the energy of an earthquake is released. Remembering that faulting is a brittle response, most earthquake foci are located at Earth's surface where the rocks are most brittle. With depth, the frequency of earthquakes decreases exponentially as the rocks become less brittle and more plastic in response to the increased temperatures and pressures. Seventy five percent of all earthquakes are referred to as shallow focus earthquakes that occur from Earth's surface to a depth of about 40 miles. You will remember that the brittle Earth's crus averages about 40 miles thick. Intermediate focus earthquakes that make up about 20% of all earthquakes occur from a depth of 40 miles down to about 200-250 miles while deep focus earthquakes occurring down to depths of about 450 miles. Earthquakes do not occur below a depth of about 450 miles because the rocks become totally plastic.

The epicenter of an earthquake is the point on Earth's surface immediately above the focus. Note that while the focus of an earthquake can be anywhere from Earth's surface down to a depth of about 450 miles, the epicenter is *always* at the surface. For earthquakes occurring at Earth's surface, the focus and epicenter are the same point. Because the epicenter is the point closest to the point of energy release, the epicenter is also the point on Earth's surface where the earthquake energy is at a maximum.

BODY WAVES and SURFACE WAVES: Body waves are those seismic waves that originate at the focus and are propagated through Earth's interior. Body waves are both shear and compression in type with both types of wave following the exact same path as they traverse Earth's interior. As shear waves propagate through a solid medium, they move the material perpendicular to the direction of propagation. Compression waves, on the other hand move the material (solid, liquid, or gas) back and forth parallel to the direction of propagation. The shear body waves are designated "s" waves while the compression body waves are designate "p" waves. The major characteristic of body waves is that they are of very low amplitude which means that the materials through which they pass experience a very small amount of movement, probably no more than a fraction of a millimeter. Because so little energy is expended moving material, significant amount of energy can be expended in moving the wave front; explaining why body waves can penetrate completely through Earth, a distance of about 8,000 miles in about 20 minutes at an average velocity of 24,000 miles per hour. Of the two types of body waves, the "p" wave has a slightly higher velocity.

When the body waves reach Earth's surface, their energy is transferred to Earth's surface at the epicenter, creating the surface waves which move out from the epicenter in all directions across Earth's surface. Surface waves are of two types: 1) Love waves and 2) Rayleigh waves. Love waves consist of the horizontal portion of shear, moving Earth's surface back and forth horizontally to the direction of propagation. The Rayleigh waves are a combination of the vertical component of shear plus the to and fro motion of compression, resulting in a rolling motion as they move across Earth's surface. While the amplitude of the body waves is very small, the amplitudes of the surface waves can be large enough to produce movement of Earth's surface that can be seen. It is quite apparent that, of the two types of seismic waves, the surface waves are responsible for the damage What is not so obvious is that of the two types of surface waves, the Love waves cause more damage than the Rayleigh waves. While the Rayleigh waves subject Earth's surface to continuous, fluid motion, the Love waves subject the surface to a rapid back and forth motion that is especially difficult for structures to absorb.

EARTHQUAKE INTENSITY and MAGNITUDE: The first comprehensive studies of earthquakes were conducted independently by two seismologists, one an Italian by the name of Mercalli and the other a Swiss named Rossi. Both were studying the intensity of earthquakes which basically refers to the observed results of the quaking and the amount of resulting damage. The result of their studies were two relative scales of damage where each step is a verbal description of what one would expect to experience or see. Because both scales were similar, their results were combined in what is referred to as the Mercalli/Rossi Scale or the Modified Mercalli Scale.

Earthquake Magnitude: The numerical evaluation one commonly hears in regard to earthquakes is, however, a totally different scale of measurement called the Richter Scale. In 1935, Charles Richter, a professor at California Institute of Technology, devised a method of evaluating the magnitude of an earthquake based on the actual amounts of earth movement and the energy released. These data were created from measurements made using a sensitive instrument called a seismograph. The Richter Scale assigns a magnitude from 1.0 to 10.0 where each next higher step in the scale represents 10X the amount of earth movement and 30X the amount of energy released than the next lower step. The frequency of earthquakes represented by the individual steps of either the Richter or Mercalli scales decreases exponentially upward. For example while hundreds of thousands of earthquakes occur yearly with Richter Scale readings from 2.0 to 2.9, only one or two may occur with a Richter Scale reading in excess of 8.0. In all of historic time, there have only been about a half dozen earthquakes recorded worldwide with a Richter Scale reading over 9.0. An earthquake with a Richter reading of 2.0 would only be felt by individuals quietly at rest while a quake in excess of 8.0 would result in major damage and potential loss of life and one in excess of 9.0 would result in .total destruction within the affected area.

LIMITING EARTHQUAKE DAMAGE: A great deal of research has gone into devising ways in which structures can be built to resist earthquake damage. Realizing that there is no structure that is "earthquake proof", ways have been tested to minimize damage.

Observations have shown, for example, that structures whose foundations are anchored in bedrock have a higher tendency to survive an earthquake than one whose foundation is in unconsolidated materials. During the 1989 Loma Prieta earthquake that struck San Francisco, one of the highly damaged areas of the city was the Marina where town houses had been built on top of sediment deposited into the Bay following the great earthquake and fire of 1906. Engineering studies have shown that water-saturated material, though compacted, has a tendency to momentarily turn to a jello-like consistency as the shock wave passes, resulting in structures to momentarily lose support and sink into the sediments.

Another characteristic of earthquake damage clearly demonstrated by the 1906 San Francisco earthquake and the effect of the Loma Preita earthquake on the Marina is that most of the damage is caused by fire. In both cases, water drained from severed water mains leaving the fire to be fought with water pumped from the bay; fires that were fed by gas escaping from severed gas mains that couldn't be turned off because valves were buried in debris.

The type of building materials can affect the amount of damage. Buildings constructed of flexible materials such as metal have a better chance of survival that buildings constructed of brittle masonry products such as block or brick. A compromise is the construction of masonry components around a metal framework that serves to distribute energy throughout the building rather that allowing it to concentrate in one place. One of the reasons why one reads about earthquakes of relatively modest magnitudes causing so much damage in developing countries is that they build homes and multi-story buildings of very brittle sun-dried brick. Without adequate structural support components within the walls, fractures quickly develop which often results in total destruction.

A common observation made following many earthquakes are adjacent buildings that appear to have been of comparable construction and yet suffered significantly different levels of damage. Because it is highly unlikely that the buildings were subjected to different levels of quaking, some other factor or factors must be involved. This has led to a theory involving the vibrational frequency of the ground in response to the seismic waves and a possible vibrational frequency of the building. Studies of earthquake vibrational frequencies shows a Gaussian distribution with one vibrational frequency occurring with the greatest intensity. According to the theory, every building will have its own vibrational frequency depending on the kinds of constructional materials and type of structure. If the vibrational frequency of the building is significantly different from that of the seismic waves, it will experience only the movement imposed by the passing seismic waves. However, if the vibrational frequency of the building the same, or nearly the same, as the maximum vibrational frequency of the seismic waves, the entire building may be set into harmonic vibration by the seismic waves. The result would be that the building would be subjected to destructive energy from without and from within. An adjacent building whose vibrational frequency was significantly different from that of the seismic waves would only be subjected to destructive forces from without. The objective would be to design buildings with frequencies that would be significantly different from the mean seismic frequency, an objective not yet achieved.

In many regions that are subjected to potentially severe earthquakes, building codes have been established to minimize the amount of earthquake damage. Until these codes were legislated, one of the major forms of damage to buildings was they would "fall off" their foundations. Rather than the building falling off the foundation, what actually happened was the horizontal movement induced by the Love waves actually pulled the foundation out from under the building. To prevent this from happening, codes now require that all new buildings be bolted to the foundation so that foundation and building move as a single unit. In the case of larger buildings, shock absorbers not unlike those used in automobiles are placed between the foundation and the building to absorb the earth movements and thereby reduce the amount of energy actually reaching the building proper.

Another potential problem during earthquakes is damage or injury resulting from free-standing objects in the building. Typical examples are hot water heaters which are easily tipped over. Gas or electric lines serving the unit may be severed and cause fires which are the major cause of earthquake damage. In earthquake-prone regions, building codes require hot water heaters to be securely strapped and bolted to the wall. The same is true for either gas or electric stoves which may be dislocated to the point where the gas or electric connections fail.

One of the most destructive earthquake-generated phenomena is the giant sea wave called a tsunami. Meaning "harbor wave" in Japanese, tsunamis are commonly referred to as "tidal waves" although they have nothing to do with the tides. Most tsunamis are created by the release of earthquake energy from vertical fault movements along zones of subduction within or along the margin of an ocean basin. Because most of Earth's zones of subduction are located around the Pacific Ocean, lands bordering the Pacific have been subjected to more tsunamis that anywhere else on Earth with Japan and the Hawaiian Islands experiencing the greatest number. The worst tsunami to hit the Japanese Islands occurred in 1896 when a wall of water estimated to be nearly 100 feet high crashed onto the eastern coastline of Honshu, sweeping away an estimated 10,000 homes and 26,000 people. Some tsunamis are generated by violent eruptions of volcanic islands. The eruption of Krakatau in 1883, for example, generated a tsunami that washed over low-lying islands and swept more than 36,000 people to their deaths.

What is amazing about tsunamis is that they cross the open sea with amplitudes not exceeding a foot or so but with speeds averaging 500 miles per hour. Upon approaching the shoreline, wave velocities slow but at the same time increase in amplitude tremendously and drive onto land at speeds over 100 miles per hour, causing enormous destruction and death.
To warn inhabitants within and around the Pacific Ocean basin, the Seismic Sea Wave Warning System (SSWWS) was established in 1946. Earthquakes anywhere within or adjacent to the Pacific basin are monitored in Honolulu, Hawaii with warnings broadcast throughout the Pacific where sirens warn the residents of their approach.

SEISMOLOGY: Seismology is the study of earthquakes and the instrument seismologists used to study earth movements is the seismograph. Like any instrument that ends in *-graph,* it is an instrument that gives a permanent record of whatever was measured in the form of a *gram.* For example, a tele*graph* gives a tele*gram.* However, before the seismograph was invented, there were seismometers. Any instrument ending in *-meter* takes a measurement, displays that measurement, but does not leave a permanent record. For example, a volt*meter* measures voltage and a speedo*meter* measures speed, but neither provides a permanent record of the measurement. The first seismometer was invented by the Chinese sometime in the 2nd century. The instrument consisted of a brass sphere around the perimeter of which were brass dragons with brass balls precariously balanced between their canine teeth. Below each dragon was a brass frog with its open mouth pointing up to the dragon. The horizontal movement of the Love waves would dislodge the balls from the mouths of those dragons facing toward or away from the direction of propagation. The balls would then fall into the mouths of the awaiting frogs. While the instrument could detect the occurrence of an earthquake as well as the two possible directions to the epicenter, it could tell little else. Unless one were present at the time the quake struck, there would be no record of its time of arrival or of its duration nor was there any means to record the actual amount of earth movement. Seismometers were the tools of the trade for nearly 1500 years.

Sometime in the mid-1700s, the first seismograph was invented that consisted of a pendulum equipped with a pointer that was suspended over a layer of fine powder. This basic design was improved upon by an Italian named Cavalleri in 1858 who used two pendulum-based instruments to record the maximum amplitude of both the horizontal and vertical earth motions. The instruments consisted basically of a ring stand from which the pendulums were suspended, one on a string, the other on a spring. A pen extending from the pendulum drew a line on a piece of paper. The passage of the Love and Rayleigh waves would move the ring stand while the pendulums, because of their inertia, would remain motionless The instrument with the pendulum suspended on a string recorded the passage of the Love wave by drawing a line on a piece of paper placed on the base of the ring stand as the instrument moved perpendicular to the direction of propagation of the Love wave.

The instrument with the pendulum suspended on a spring recorded the passage of the Rayleigh wave by drawing a line on a piece of paper attached to the upright of the ring stand that would move vertically as the seismic wave passed by. It is this relative motion between the moving instrument and the motionless pendulum that allows the seismic wave to be recorded. Although quite an advancement over the Chinese seismometer, the major short coming of all the seismographs of the day was the fact that they could not record any <u>time-related</u> component of the earthquake. It could not, for example, record the time of arrival of the first seismic waves or the duration of the tremor nor could it record the wavelength of the seismic wave or the change of amplitude or wavelength over time.

The problem of recording time-related events was solved in the late 1800s by an English engineer by the name of John Milne who had been hired as a professor of geology and engineering at the University of Tokyo, Japan. Being subjected to a multitude of earthquakes and being aware of the limitations of the available instruments, Milne invented an instrument that would record the timing of the seismic events. Milne replaced the flat recording surface with a cylinder to which the recording paper was attached. To record the horizontal motions of the Love waves, Milne designed an instrument with the pendulum suspended horizontally while the vertical movement of the Rayleigh waves was recorded with a vertical pendulum instrument comparable to Cavalleri's. As in the older instruments, a recording pen extended out from the pendulums and scribed a line on the cylinder. The cylinder was then *rotated* and *translated* along its axis by a clock mechanism that allowed the recording pen to scribe a timed, spiraling line on a piece of paper wrapped around the cylinder. When removed from the cylinder and laid flat, the resultant seismogram .recorded the seismic history over a period of time. With the exception of taking advantage of modern electronics and computers, the modern seismograph is basically identical in design to the one invented by Milne more than a century ago.

The basic modern seismic station consists of two horizontal-pendulum instruments and one vertical pendulum instrument. The reason for two horizontal instruments is because a Love wave approaching perpendicular to the axis of the instrument will move the entire instrument, including the pendulum, and, as a result, cannot be detected. However, by orienting two horizontal pendulum instruments at right angles to each other, Love waves approaching from any direction can be recorded. The vertical motion of the Rayleigh waves is recorded by the vertical pendulum instrument. Most seismic stations have at least three sets of instruments designed to respond to a range of vibrational frequencies from high to low.

Another important aspect of seismograms is that they are accurately timed by the recording of a signal sent out from synchronized cesium clocks, one of which is located at the Bureau of Standards at Fort Collins, Colorado. The fact that all seismographs world-wide are tuned to the same clock allows seismograms from around the world to be compared.

The two bits of information a seismologist wants to glean from every seismogram are: 1) where was the epicenter and focus and 2) what was the magnitude of the earthquake at the epicenter. Let us first consider the question of the location of the epicenter by assuming the earthquake originated at Earth's surface. From the moment the energy was released, the body and surface waves propagate in all directions and finally arrive at a seismic station where they are recorded. Because of their high velocities (24,000 mph), the body waves will always arrive before the surface waves and are recognized by their very small amplitudes compared to the surface wave record. Previously we noted that body waves are of two types, the shear waves designated "s" waves and the compression waves designated "p" waves. Both types of body waves follow the exact same path through Earth from the focus to the seismic station with velocities that are accurately known. The major difference in the two types of body waves is that the velocity of the "p" waves is slightly higher that the velocity of the "s" wave, resulting in the "p" wave always arriving shortly before the "s" wave. Considering the passage of the body waves to be a race that the "p" wave will always win, one can make a graphic display of their individual race performance by plotting time versus distance traveled, a so-called time-travel curve. Once in possession of such a plot, one can accurately determine the difference in the arrival times of the two waves and, using the time-travel plot, determine how far back the race started, in other words, the distance to the focus. A circle drawn on a map centered on the location of the seismic station with the determined distance to the focus will locate the focus of the earthquake relative to the seismic station. By repeating the process with data acquired from at least two other seismic stations, the exact location of the focus will be at the point where the three circles intersect. If the focus of the earthquake was at Earth's surface, the circles will intersect at a point which and in this case, is both the focus and the epicenter,. If the focus is at some depth, the intersection of the three circles will be in the form of a spherical triangle, the center of which would be the epicenter. By considering the construction in three dimensions, the circles are in reality the surface expression of three hemispheres that intersect at a single point. Using the dimension of the sides of the triangle, the depth to the point of intersection can be calculated, thereby locating the focus.

The magnitude of the earthquake at the epicenter can be determined from the data recorded at a single seismic station. Because the epicenter is immediately above, or at, the focus, the amplitude of the surface waves will be at a maximum at the epicenter and decrease away from the epicenter in a mathematically predictable fashion. If one were able to determine the amplitude of the surface waves at a particular seismic station and knew how far away the earthquake occurred, one should be able to calculate the amplitude of the surface waves at the epicenter. Because the Richter Scale reading is a function of the amount of earth movement, the calculated epicenter amplitude should be easily converted to a Richter Scale reading. The distance to the epicenter is determined by the "p"-"s" arrival times of any three stations. The movement of Earth's surface in the vicinity of a seismic station is recorded by the surface wave arrivals. For each specific seismograph, the actual seismic wave amplitude can be calculated from the amplitude of the surface wave recording using information provided with the instrument. With the change in surface wave amplitude away from the epicenter being known, the actual seismic wave amplitude at any seismic station and the distance to the epicenter can be used to calculate the seismic wave amplitude at the epicenter. With that information, the Richter Scale reading can be calculated. Because all of the calculations all relatively straight forward, a nomograph can be generated to make all the necessary calculations graphically. The nomograph consists of three scales, one being the difference in the time of arrival of the "p" and "s" body waves in seconds, the second the amplitude of the surface waves in millimeters, and the third, the magnitude of the earthquake at the epicenter. By drawing a line from the arrival time scale to the amplitude scale, the point where it crosses the magnitude scale gives the magnitude of the earthquake at the epicenter.

EARTHQUAKE PREDICTION

Like so many geologic events including volcanic eruptions and slope failures, earthquakes cannot be predicted with the level of precision that would be of use to those potentially involved. Attempts to predict earthquakes fall into two categories, short term and long term. Of the two, short term predictions would be of the greatest interest to individuals living in earthquake-prone areas in that they would give adequate warning for evacuations to take place. Much effort has gone into attempting to establish a set of criteria that would allow such predictions to be made. One such study involved determining whether a major earthquake is preceded by a sequence of events or ground movements that could be detected by sensitive seismographs tiltmeters, or creepmeters. In 1975, the Chinese reported the accurate prediction of an earthquake that struck Liaoning Province that allowed thousands of people to be evacuated. They reportedly used unusual animal behavior as the criteria based on the often observed fact animal living in regions about to experience a natural disaster such as an earthquake, landslide, or avalanche become jittery an do weird things. Apparently, the basis for the prediction and subsequent evacuation were such observations coupled by the fact that animals come out of hibernation. Unfortunately, a year later, a quarter of a million people died in an unpredicted earthquake in the same province.

After all of the efforts to establish short term predictive criteria, the conclusion has been reached that the degree of certainty needed to predict with the precision and without the occurrence of false alarms required by the population of an earthquake-prone region simply cannot be achieved, at least not in the foreseeable future.

Long term predictions are based on the idea that fault movements are cyclic with recognizable intervals of seismic quiet. Seismic gaps are those portions of fault zones along which earthquakes have not occurred for the better part of a century. One would predict future fault movement to be more likely within the seismic gaps than elsewhere. There are other fault segments that have been identified as being especially prone to movement. One such segment of the San Andreas Fault Zone is in the locality of Parkfield, California, where records kept for about 150 years have shown a history of frequent earthquake activity.

Although the long term predictions that are being made will not provide a sense of security in the populations living in earthquake prone regions, they have served to initiate building codes that will make structures less prone to damage and therefore more safe for the people who live and work in them.