About 80% of all earthquakes occur in the circum-Pacific belt, and 15% within the Mediterranean-Asiatic belt. The remaining 5% occur largely along oceanic spreading ridges or within plate interiors.
EARTHQUAKES and SEISMIC WAVES

• What is an earthquake?
• Elastic Rebound Theory
• Seismology
• The Frequency and Distribution of Earthquakes
• Seismic Waves
• Locating an Earthquake
• Measuring the Strength of an Earthquake
• The Destructive Effects of Earthquakes
• Earthquake Prediction
• Earthquake Control
EARTHQUAKES AND SEISMOLOGY

• Geologists define an earthquake as the shaking and trembling of the ground caused by the sudden release of energy, usually as a result of faulting, which involves displacement of rocks along fractures.

• Seismology is the scientific study of earthquakes.

• The elastic rebound theory states that rocks rupture when pressure accumulating in rocks builds to a level which exceeds the rocks' strength.

• Stored energy of the accumulated pressure is released as the faulted rocks snap back to their original position, but offset along a fault line.

• The focus is the point where an earthquake's energy is released.

• The epicenter is that point on the surface vertically above the focus.
Elastic Rebound Theory was proposed by H.F. Reid from studying the effects of the 8.3 magnitude earthquake that occurred in 1906 along the San Andreas fault near San Francisco.


- Points on opposite sides of the fault moved ~3.2 meters over a 50-year period prior to the event.

- Eventually, the internal strength of the rock is exceeded and the rocks snap back into shape, leaving a rupture along a fault line.

- An analogy for the manner in which rocks hold elastic energy is a watch spring: the tighter the spring is wound, the more energy is stored, thus making more energy available for release.

- Another analogy is bending a stick until it snaps.
EARTHQUAKE STICK-SLIP MOVEMENT

- When the force trying to make the block (m) slip becomes greater than the frictional force causing it to stick, the block will slip.
ELASTIC REBOUND THEORY

- Snap back (elastic rebound) causes the vibrations
- Build up of stress can cause small quakes - foreshocks before the big one
- Also can have aftershocks after main quake as rocks readjust
EARTHQUAKE AND FAULT TERMINOLOGY

Epicenter B
Hypocenter B
Epicenter A
Hypocenter A

FOOT WALL
Fault surface
Seismic wave
Hanging Wall

W. W. Norton
EXAMPLE OF EARTHQUAKE FAULT SCARPS

1959 Hebgen Lake earthquake, Montana
EXEMPLARY OF AN EARTHQUAKE FAULT SCARP

What side of the fault is the person standing on?

Footwall
Fault surface
Hanging wall
SLIP LINEATION ON A FAULT SURFACE

• Many brittle faults show slip lineation from simultaneous rock slip and abrasion and/or mineral crystallization.
FAULT SCARP VERSUS ‘BLIND’ FAULTS

• Many faults never break the surface, and form overlying folds in strata.
95% of earthquakes occur at tectonic plate boundaries where rocks converge, diverge, or slip past each other.
Distributed fault planes are profiled using earthquake focal points that correspond to the center of elliptical fault planes of varying size and orientation.
EARTHQUAKES AND SEISMOLOGY

Convergent margin subduction zone

- shallow: 20 km
- intermediate: 300 km
- deep: 660 km

Earthquake focus
Epicenter
EARTHQUAKES AND SEISMIC WAVES

• Earthquake vibrations or seismic waves are of two kinds:

1) **Body waves travel through Earth** *(faster than surface waves)*
   a. *P-waves* are compressional waves and travel faster than *S-waves*
   b. *S-waves* are shear waves that cannot travel through liquids

2) **Surface waves travel along or just below the surface** *are slower and more destructive than body waves, and are divisible into two types:*
   a. *Rayleigh waves* – circular, up-and-down motion
   b. *Love waves* – sideways motion
EARTHQUAKES BODY WAVES

P-waves

S-waves

Wavelength

Compression  Dilation

Direction of Propagation

Particle Motion

Wavelength

Direction of Propagation

Particle Motion
EARTHQUAKES SURFACE WAVES

Love wave

Rayleigh wave

Ground surface

Wave propagation

Direction of Propagation

 LOVE WAVE

RAYLEIGH WAVE

Particle Motion
EARTHQUAKES SURFACE WAVES

- **The Northridge earthquake**, 01/17/1994, Los Angeles, California lasted for about 10–20 seconds and had one of the highest ever ground acceleration instrumentally recorded in an urban area in North America.

- Strong ground motion felt as far away as Las Vegas, Nevada, about 220 miles (360 km) from the epicenter.

- 57 people killed, and over 8,700 injured.

- An estimated $20 billion in damage, making it one of the costliest natural disasters in U.S. history.
EARTHQUAKES SURFACE WAVES
EARTHQUAKES SURFACE WAVES
RELATIVE VELOCITIES OF BODY AND SURFACE WAVES
MODIFIED MERCALLI INTENSITY SCALE

• An earthquake's intensity is a measure of the kind of damage which occurs, and is expressed on a scale of I to XII known as the Modified Mercalli Intensity Scale (1902).

Giuseppe Mercalli (1850 –1914) was an Italian volcanologist and Roman Catholic priest. He is best remembered today for his Mercalli intensity scale for measuring earthquakes which is still used today.

Defined by amount of destruction and depends on earthquake strength, distance from the epicenter, surface materials, and building design.
SEISMOGRAFPHS

• The record of an earthquake, a seismogram, is made on a seismograph.

Seismographic stations have three different seismographs that measure ground motion along three principal axes: X (east-west), Y (north-south) and Z (up-down or vertical).
SEISMOGRAPHS

Before earthquake

Ground and frame sink.

Ground and frame rise.

Reference line

Paper

Time (minutes)

11:00
12:00
1:00
2:00
3:00

25 30 35 40 45 50 55 60

W. W. Norton
SEISMOGRAPHS
SEISMOGRAPHS

- By measuring and plotting on a time-distance graph the P- and S-waves received at three seismograph stations, the epicenter of an earthquake can be located.
THE RICHTER SCALE

• The magnitude of an earthquake is a measure of the amount of energy released and was first expressed using the Richter Magnitude Scale.

• The magnitude is determined by measuring the seismic wave of maximum amplitude and plotting the value on surface-wave magnitude scale.

• The measured time difference (seconds) between the P- and S-wave arrivals determines the Body-wave magnitude scale.

• A line is drawn connecting the body-wave and surface-wave scale that crosses the Magnitude scale, that is a linear plot starting at 1.

• The body- and surface-wave scales use logarithmic scales (non-linear), meaning that the scale markings are not uniform and increase using an exponential factor.

• Each integer increase in magnitude therefore records about a 30-fold increase in energy released.

Richter quote: "logarithmic plots are a device of the devil"
THE RICHTER SCALE (MS and Mb)

A former measure of earthquake magnitude

• In 1935, Charles Richter and Beno Gutenberg (Cal Tech) developed the Richter scale for quantifying medium-sized earthquakes (between magnitude 3.0 and 7.0) in Southern California.

• This scale was tightly constrained by earthquake size and epicenter-distance limits that made it unreliable for large earthquakes at great distances (>600 km) from the epicenter. But the scale was simple to use and corresponded well with observed damage for many seismic events. It gained common acceptance despite being inadequate for characterizing some classes of earthquakes.

• A modified Richter scale was developed by Beno Gutenberg as an expansion of their earlier work to account for earthquakes detected at distant locations. At such large distances the higher frequency vibrations are attenuated and seismic surface waves (Rayleigh and Love waves) are dominated by waves with a period of 20 seconds (which corresponds to a wavelength of about 60 km). Their magnitude was assigned a surface wave magnitude scale (MS). Gutenberg also combined compressional P-waves and the transverse S-waves (which he termed "body waves") to create a body-wave magnitude scale (Mb), measured for periods between 1 and 10 seconds. Ultimately Gutenberg and Richter collaborated to produce a combined scale which was able to estimate the energy released by an earthquake in terms of MS.

• The Richter Scale, as modified, was successfully applied to characterize localities. This enabled local building codes to establish standards for buildings which were earthquake resistant. However a series of "great earthquakes" happened from faults that broke along long lines of up to 1000 km long that resulted in scaling problems. The MS scale was unable to characterize great earthquakes that produced very-long-period waves (more than 200 s) which carried large amounts of energy. As a result, use of the modified Richter scale methodology, to estimate earthquake energy, was also deficient at high energies.
THE MOMENT MAGNITUDE SCALE (MW)


- This method proposed that the energy release from a quake is proportional to the surface area that breaks free, the average distance that the fault is displaced, and the rigidity of the material adjacent to the fault.

- This approach is found to correlate well with the seismologic readings from long-period seismographs.

- Hence the moment magnitude scale (MW) is often used to compare the size of all different earthquakes, including the ‘great’ ones.

  - Seismic moment is the basis of the MW and is defined the equation: \( M_0 = \mu AD \), where

    \( \mu \) is the shear modulus of the rocks involved in the earthquake (dyne/cm\(^2\))

    \( A \) is the area of the rupture along the geologic fault where the earthquake occurred (in cm\(^2\)), and

    \( D \) is the average displacement on \( A \) (in cm).
## COMPARISON OF RICHTER AND MOMENT (MW) MAGNITUDES

<table>
<thead>
<tr>
<th>Quake</th>
<th>Richter</th>
<th>Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1964</td>
<td>8.4</td>
<td>9.2</td>
</tr>
<tr>
<td>1906</td>
<td>8.3</td>
<td>7.9</td>
</tr>
</tbody>
</table>
ELASTODYNAMIC EARTHQUAKE ANALYSIS

- Uses moment tensors to describe the nature of elastic strain at the focal source derived from many observation points on land surface, such as seismographic stations located as various distance to a source.

- First-motion wave polarity acquired at many seismic stations helps determine the different seismic sectors and the geometry of fault dislocations at the source event.
DETERMINATION OF NODAL PLANES

- A network of seismic stations surrounding an earthquake occurring on a vertical plane (90° dip) will show an arrangement of first-motion polarities divided among four sectors oriented at right angles to one another (orthogonal arrangement) separated by two nodal planes, hence, a *double couple*.

- One of these nodal planes is the *fault plane* and the other is known as the “auxiliary plane”.

*Unfortunately, first-motion studies can only tell us about the geometry of the rupture, but not which of the two planes is the fault. That can only be determined or inferred by the tectonic setting or where faults emerge at the ground surface.*
EARTHQUAKE ON A VERTICAL PLANE

→ DIRECTION OF FIRST MOTION
○ FIRST MOTION IS PUSH (COMPRESSION)
○ FIRST MOTION IS PULL (DILATATION)

⊗ NO FIRST MOTION (UNDEFINED)

A $\mathbf{S}_B$ SLIP VECTOR SHOWING MOTION OF PLATE B RELATIVE TO PLATE A

courtesy of Ian Hill, University of Leicester, UK
SPREADING OF THE SEISMIC WAVE
LOCATING AND CHARACTERIZING A SEISMIC EVENT

• The **take-off angle** and **azimuth** are used to locate the depth of the event.

• The **seismic moment** is used to describe the nature of the event.

![Diagram showing the take-off angle and seismic moment.]

Stein and Wysession, *An Introduction to seismology, earthquakes and Earth structure*
THE AZIMUTH ($\phi$) AND TAKE-OFF ANGLE are used to precisely locate a unique seismic focal point on a sphere.

Diagram showing how to locate a seismic event using the azimuth and take-off angle with a stereographic projection.

Diagram showing primary seismic body-wave ray paths emanating from a surface source and following diffraction patterns through Earth’s mantle and core.
THE SEISMIC MOMENT TENSOR

• The pattern of energy radiated during an earthquake with a single direction of motion on a single fault plane may be modeled as a double couple force system and the equivalent force dipoles (P & T) which is a mathematical system known as the moment tensor.

• The moment tensor solution is typically displayed graphically using a so-called beachball diagram.
THE SEISMIC MOMENT TENSOR

• Many aspects of the event waveform are analyzed and combined with first-motion data to ‘invert’ the composite dataset and derive a **moment tensor** that describes the nature of elastic strain resulting from the seismic moment at the focal source with respect to a coordinate reference frame.

\[
d_n(x, t) = M_{kj} \left[ G_{nk,j} \ast s(t) \right] \quad (3)
\]

\[
M_{kj} = \begin{bmatrix}
M_{xx} & M_{xy} & M_{xz} \\
M_{yx} & M_{yy} & M_{yz} \\
M_{zx} & M_{zy} & M_{zz}
\end{bmatrix}
\]

• The constant \( M_{kj} \) (a unit of a moment of force) is a symmetric 3 x 3 tensor array containing six independent elements that describe elastic strain along three principal axes.

• The components of the moment tensor can be thought of dipoles (red dumbells) oriented along three axes (columns of \( M_{kj} \)) on which ends forces (black arrows) act along the three spatial dimensions (rows of \( M_{kj} \)).

• On the top left-to lower-right diagonal, the forces act parallel to the dipole axes.

• For the other elements, the forces act around the dipole leading to a torque about an axis perpendicular to the plane containing the force and the dipole.
STEREOGRAPHIC DIAGRAMS

- A method of projecting half a sphere onto a circle.
- Vertical planes cutting through the sphere plot as straight lines
- Dipping planes are curved lines
Lines projects as points

Fault strike 109° dip 55° SW

Planes projects as arcs
FOCAL-MECHANISM DIAGRAMS (BEACHBALL DIAGRAMS)

• With enough stations the sphere around the focus will define regions of dilation and compression that define the two nodal planes.
• This sphere is then represented as the focal mechanism diagram using the stereographic projection.
• The focal mechanism diagram is therefore a graphical representation of an earthquake seismic moment.
04/12/26 00:58:50.76
OFF W COAST OF NORTHERN SUMATRA
Epicenter: 3.298 95.778
MW 8.2

USGS MOMENT TENSOR SOLUTION
Depth 7 No. of sta: 31
Moment Tensor: Scale 10**21 Nm
Mrr= 0.91 Mtt=-0.89
Mff=-0.02 Mtc= 1.78
Mrf=-1.55 Mtf= 0.47
Principal axes:
T Val= 2.53 Plg=55 Azm= 50
N 0.09 8 308
P -2.61 34 213

Best Double Couple: Mo=2.5*10**21
NF1: Strike=274 Dip=13 Slip= 55
NF2: 130 79 98
MOMENT TENSOR REPRESENTATION

Types of ‘beachball plot’ associated with different fault end-members
(nodal plane in red parallel to fault)
THE SEISMIC MOMENT TENSOR

• Earthquakes not caused by fault movement, such as underground nuclear explosions have isotropic patterns of energy radiation, with isotropic seismic moment tensors that are easily discriminated from double-couple responses.

• This is an important part of monitoring to discriminate between earthquakes and explosions for the Comprehensive Test Ban Treaty.
INDUSTRY APPLICATIONS OF THE SEISMIC MOMENT TENSOR

Seismic Moment Tensor Inversion (SMTI)

Event locations and magnitudes give limited insight into the processes that control the growth and dynamics of hydraulic fractures. Our understanding of reservoir behaviour can be enhanced by considering the seismic moment tensor representations of these events, which serve as a direct snapshot of the instantaneous deformation of the surrounding rock by the seismicity.

When an event occurs, the rock has experienced some form of failure. Seismic moment tensors are able to describe whether the failure is shearing or tearing (i.e. mode II or mode III failure), if a change in volume has occurred (i.e. opening or closing fractures) or some combination of these scenarios.

Seismic moment tensors (SMTs) are represented by “beachballs”. The pattern on the symbol indicates the type of failure which occurred and the colour represents the relative proportion of double-couple (DC), isotropic (opening or closing) and compensated linear vector dipole (CLVD) modes.

The characteristic beachball design scheme and orientation of the moment tensors represent the strain at the source. The coloured sections of the beachball are in tension while the white sections are being compressed. This deformation is also described by the tension axis (blue, outward arrow) and the pressure axis (red, inward arrow).

Benefits of SMTI Analysis:

- Characterize microseismic event failures
- Advanced understanding of fracture propagation
- Identify which fractures are contributing to production
- Increased knowledge of fracture networks
- Provides insight into fracture effectiveness
- Characterize stimulated volumes and surfaces
- Estimate fluid flow enhancement
- Understand stress-strain field and fracture orientations

Microseismic events expressed as moment tensors for a horizontal hydraulic fracture
THE DESTRUCTIVE EFFECTS OF EARTHQUAKES

• GROUND SHAKING
• FIRES
• GROUND FAILURE
• TSUNAMIS
GROUND SHAKING

- Collapsed building, highways, and
- Liquefaction (water-saturated sediment becomes mixed and destabilized, or liquefies to behave like a fluid)
LIQUEFACTION

1964 Alaska Earthquake
GROUND FAILURE

• Earthquake-triggered landslides, faults, and rifts
**TSUNAMI’s** are earthquake-generated sea waves with up to meters amplitude.

- Most tsunamis are caused by shallow submarine earthquakes.
TSUNAMI’s – The Sumatra 2004 and 2005 seismic events in the northeast Indian Ocean
TSUNAMI’s – The Sumatra 2004 and 2005 seismic events and associated tsunami’s – more than 200,000 casualties

- Killer tsunamis are commonly caused by great (magnitude 7–8) earthquakes.
- Fault motion produced ocean bottom deformation, which generated the tsunamis.
Numerical simulation of the December 2004 tsunami in Indian Ocean

Kenji Satake, Geological Survey of Japan, AIST

Prior to the magnitude 9.0 December 2004 tsunami that devastated countries along the Indian coast, the last large tsunami to strike Indonesia occurred in 1861.

While the slow accumulation of stress makes earthquakes inevitable, accurately locating where and when rupture will occur is difficult and boils down to determining where gaps in seismic activity historically may exist along major faults.

Physics Today, June, 2005
Normal sea

Sea suddenly retreats

TSUNAMI!
TSUNAMI’s

The maximum run-up heights of tsunamis can exceed 10 m, and in small valleys on nearby land wave height’s can reached 30 m.

- Geologists use tsunami data to study old earthquakes.
- For example, a tsunami deposit was recently found that provided evidence for an earthquake occurring in the Seattle, Washington area about 1000 years ago.  EOS, January 4, 1994.
A record of a deep earthquake:

On early June 9, 1994, an exceptionally large earthquake occurred 630 km beneath a remote area in the Amazon rainforest of northern Bolivia.

Strong ground motion was felt within minutes over much of central South America.

Remarkably, ten to twenty minutes after the rupture, ground motion from it was felt by many people in the Caribbean and the North American continent, from cities as far away as Seattle, Washington, Minneapolis, Minnesota, Chicago, Illinois, and Toronto, Canada.

The earthquake had a magnitude of 8.3 and was probably caused by downward rupture on a steeply dipping east-west fault, with slip in the dip direction.

*EOS, June 28, 1994.*
GREAT EARTHQUAKES

<table>
<thead>
<tr>
<th>Year</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>1960</td>
</tr>
<tr>
<td>2.</td>
<td>1964</td>
</tr>
<tr>
<td>3.</td>
<td>2004</td>
</tr>
<tr>
<td>4.</td>
<td>1952</td>
</tr>
<tr>
<td>5.</td>
<td>2010</td>
</tr>
<tr>
<td>6.</td>
<td>1906</td>
</tr>
<tr>
<td>7.</td>
<td>1965</td>
</tr>
<tr>
<td>8.</td>
<td>2005</td>
</tr>
<tr>
<td>9.</td>
<td>1950</td>
</tr>
<tr>
<td>10.</td>
<td>1957</td>
</tr>
<tr>
<td>11.</td>
<td>2007</td>
</tr>
<tr>
<td>12.</td>
<td>1938</td>
</tr>
<tr>
<td>13.</td>
<td>1923</td>
</tr>
<tr>
<td>14.</td>
<td>1922</td>
</tr>
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</table>
RECENT AND CURRENT RESEARCH ON EARTHQUAKES

Recent research related to the moment magnitude scale focuses on:

• ways to extend the moment magnitude scale accuracy for high frequencies, which are important in localizing small quakes.

• Earthquakes below magnitude 3 scale poorly because the earth attenuates high frequency waves near the surface, making it difficult to resolve quakes smaller than 100 meters.

• By use of seismographs in deep wells this attenuation can be overcome.

• Timely earthquake magnitude estimates allow for early warnings of earthquakes and tsunamis.

• Such earthquake early warning systems are operating in Japan, Mexico, Romania, Taiwan, and Turkey and are being tested in the United States, Europe, and Asia.
EARTHQUAKE BELTS

Shallow focus <20 km  Intermediate 20-300 km  Deep >300 km
EARTHQUAKE CAUSED BY FLUID INJECTION INTO DEEP WELLS

Deepest wells ever drilled! 12.5 km
EARTHQUAKE PREDICTION AND CONTROL

• Earthquake precursors – Earthquakes can be predicted by gaps in the historical record and are often preceded by short- or long-term changes within the Earth including:
  
  • Changes in the tilt or elevation of land
  
  • Fluctuation of water-well-levels
  
  • Fluctuations or changes in the magnetic field, electrical conductance or resistance of the ground, and/or the ground volume (dilatancy)
  
• Earthquake prediction research programs are being conducted in the United States, Russia, China, and Japan, but related studies indicate that most people would probably not heed a short-term earthquake warning.

• One promising means of earthquake control is by fluid injection along locked segments of an active fault.
EARTHQUAKE PREDICTION

- Seismic risk maps – indicate the likelihood and potential severity of future earthquakes based on an analysis of historic records and the distribution of known faults.