NPTEL ONLINE CERTIFICATION COURSES

EARTHQUAKE SEISMOLOGY

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Module 09 : Earthquakes, focal mechanisms, moment tensors.
Lecture 01: Elastic Rebound Theory, Seismic Cycle and Fault Geometry

CONCEPTS COVERED

- Earthquakes
- Elastic Rebound Theory
  - Seismic Cycle
- Focal Mechanism
  - Fault Geometry
  - Classification Of Faults
- Summary

Earthquake

Turkey Earthquake , 2023; Mag: 7.8

Earthquake

Bhuj Earthquake , 2001; Mag: 7.6

Blind fault………. Unexpected

Earthquake

Sumatra Earthquake, 2004; Mag: 9.1:

Led to Tsunami as well

Earthquake

Japan Earthquake, 2011; Mag: 9.0

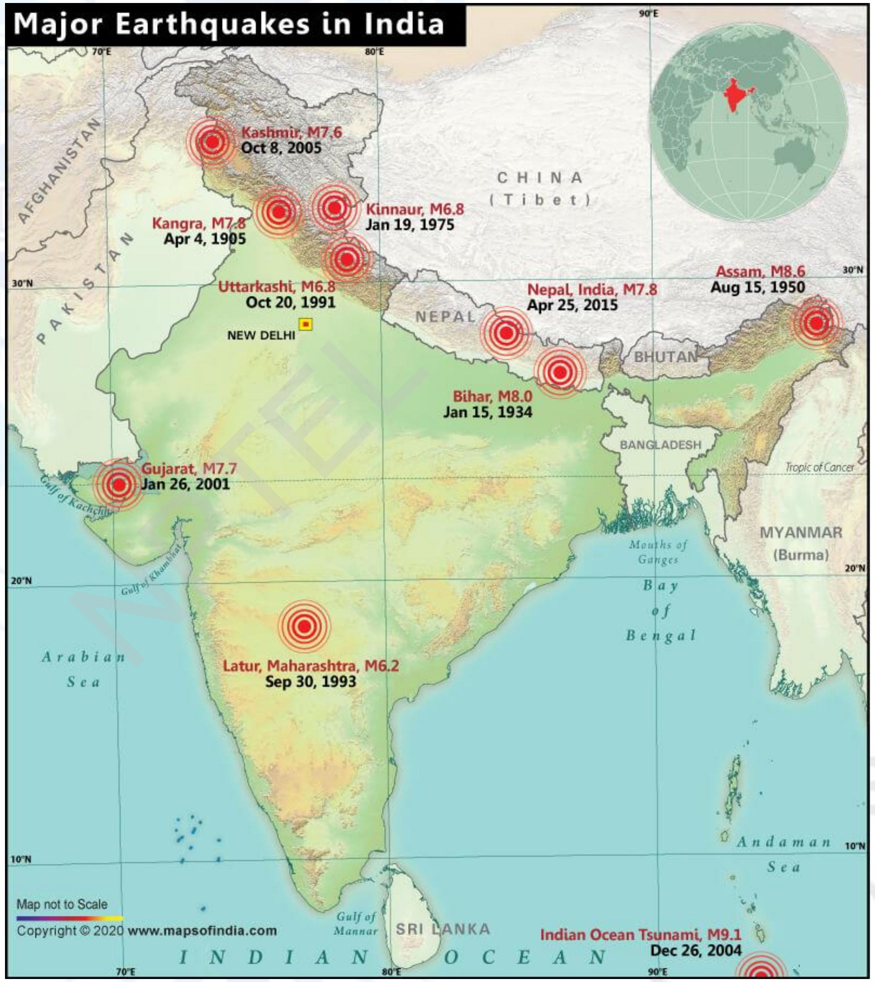
Led to Tsunami as well and explosion

Earthquake

2016 Kaikōura earthquake was a magnitude 7.8 (M_w) earthquake in the South Island of New Zealand

Some Major Earthquakes in India

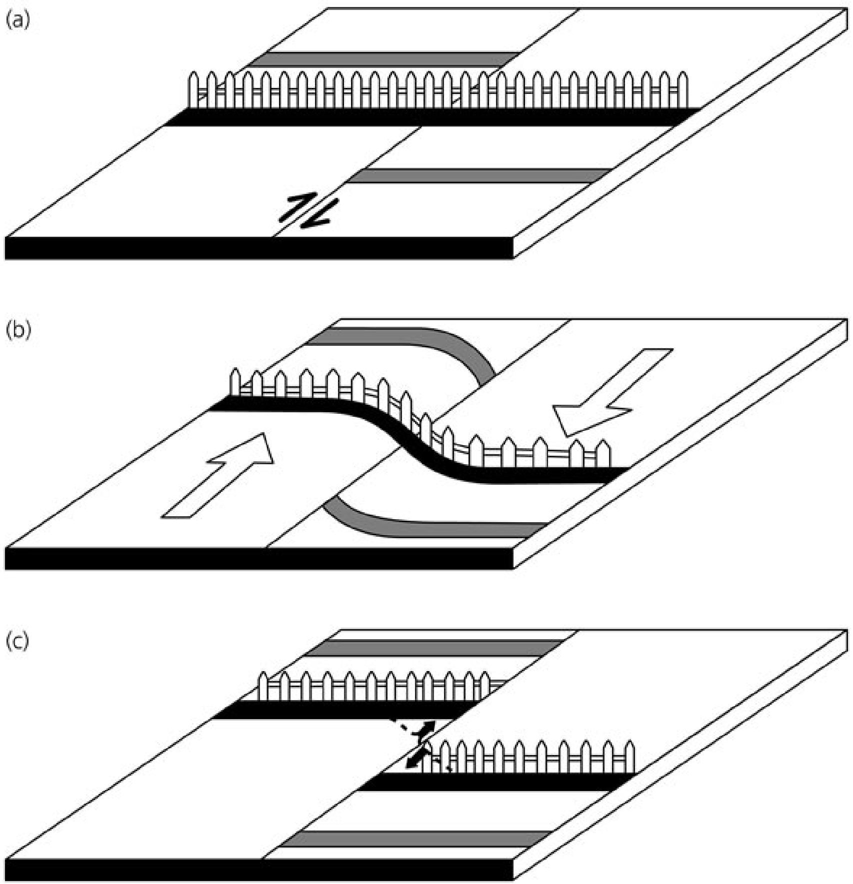
- Kangra 1905, M7.8
- Bihar 1934, M8.0
- Assam 1950, M8.6
- Kinnaur 1975, M6.8
- Uttarkashi 1991, M6.8
- Latur 1993, M6.2
- Kashmir 2005, M7.6
- Nepal 2015, M7.8



Elastic Rebound Theory

H. Reid proposed the elastic rebound theory of earthquakes on a fault

Figure 4.1-3: Cartoon of the elastic rebound model for a strike-slip earthquake.



- Materials at distance on opposite sides of the fault move relative to each other, but friction on the fault “locks” it and prevents the sides from slipping.

- Eventually the strain accumulated in the rock is more than the rocks on the fault can withstand, and the fault slips, resulting in an earthquake.

Elastic Rebound Theory

- **The elastic rebound idea was a major conceptual breakthrough, because the faulting seen at the surface had been previously regarded as an incidental side effect of an earthquake, rather than its cause.**

- **Using elastic rebound theory, we think of them as reflecting the most dramatic part of a process called the seismic cycle, which takes place on segments of the plate boundary over hundreds to thousands of years.**

- **During the interseismic stage, which makes up most of the cycle, steady motion occurs away from the fault but the fault itself is "locked," although some aseismic creep can also occur on it.**

Elastic Rebound Theory : Seismic Cycle

Inter-seismic Stage

long periods between large earthquakes during which elastic strain accumulation occurs in the broad region

Preseismic stage (Nucleation)

Associated with small earthquakes (foreshocks) or other possible precursory effects.

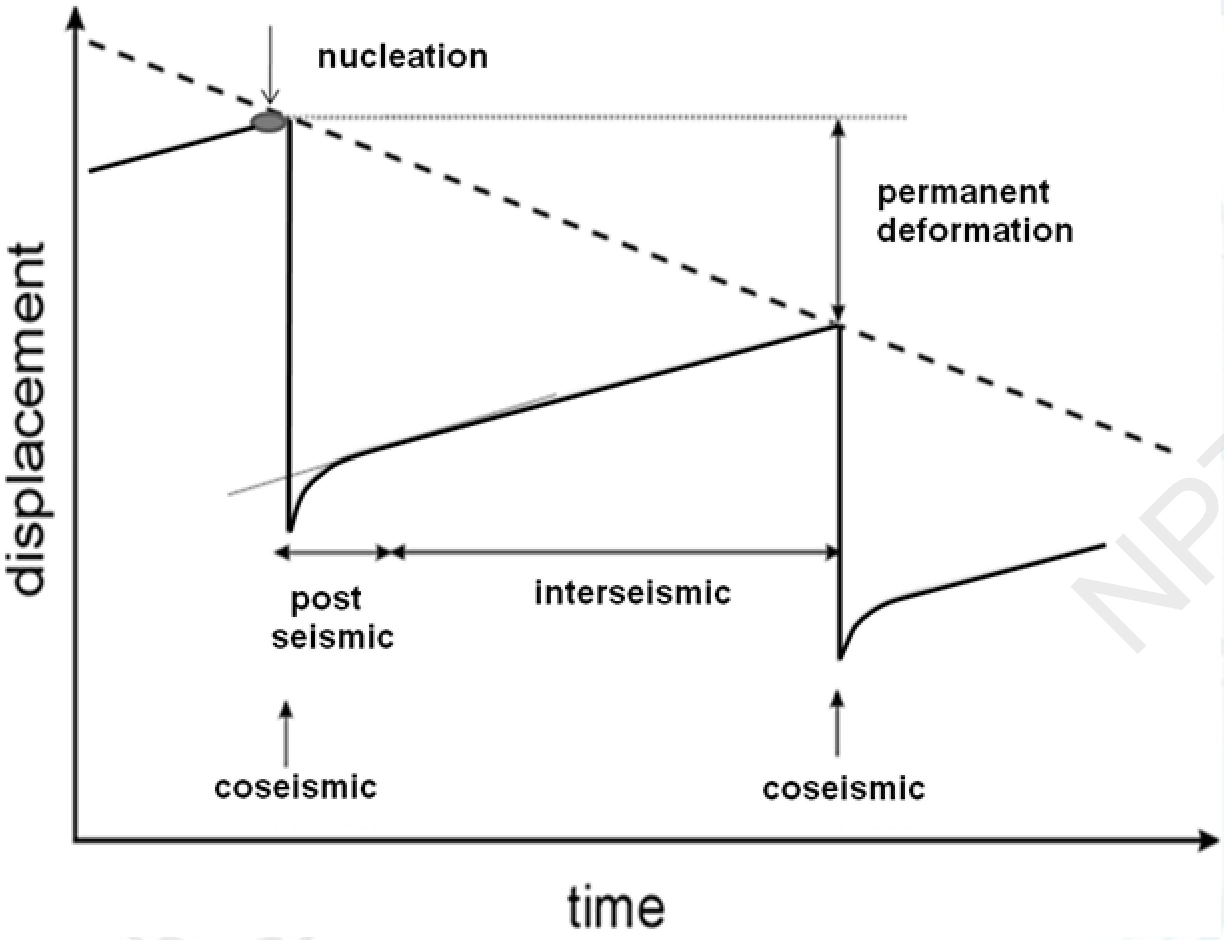
Coseismic phase

Rapid motion on the fault generates earthquakes which produces seismic waves.

Postseismic phase

Occurs after the earthquake, and aftershocks and transient afterslip occur for a period of years before the fault settles into its steady interseismic behavior again.

Elastic Rebound Theory : Seismic Cycle



During these few seconds, meters of slip on the fault "catch up" with the few mm/yr of motion that occurred over hundreds of years away from the fault.

Why to study earthquakes?

- reflect the motions of lithospheric plates and may important information about how and why plates move.

- to understand the fundamental physics of earthquake faulting and large-scale geological processes causing earthquakes.

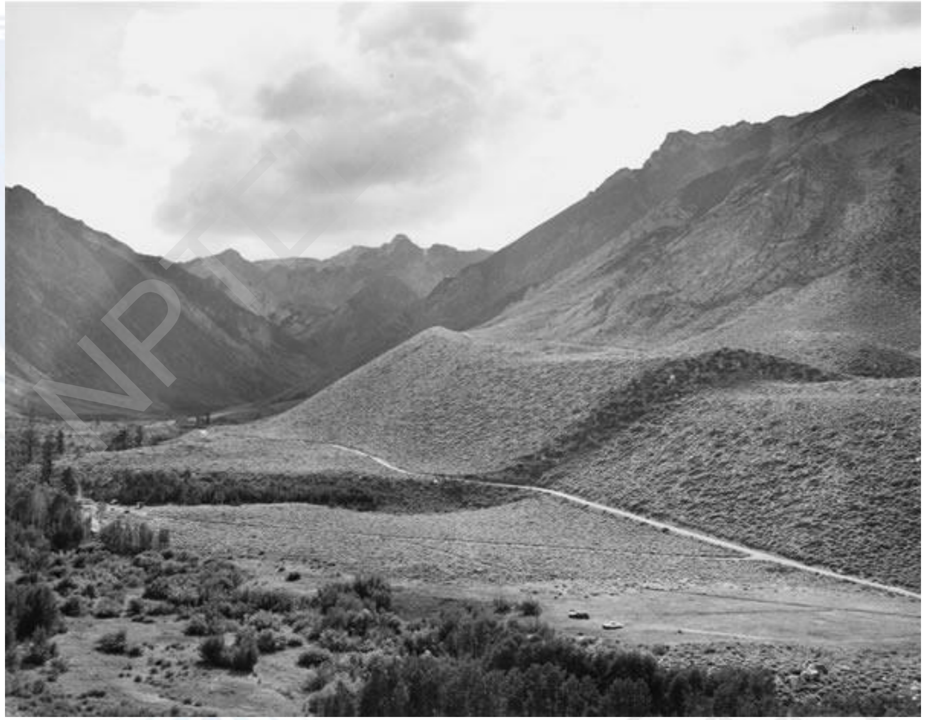
- knowledge of earthquakes can help mitigate the risk they pose.

Focal Mechanisms: Fault Geometry

- To describe the geometry of a fault, we assume that the fault is a planar surface across which relative motion occurred during an earthquake.

- Geological observations of faults that reach the surface show that this is often approximately the case, although complexities are common.

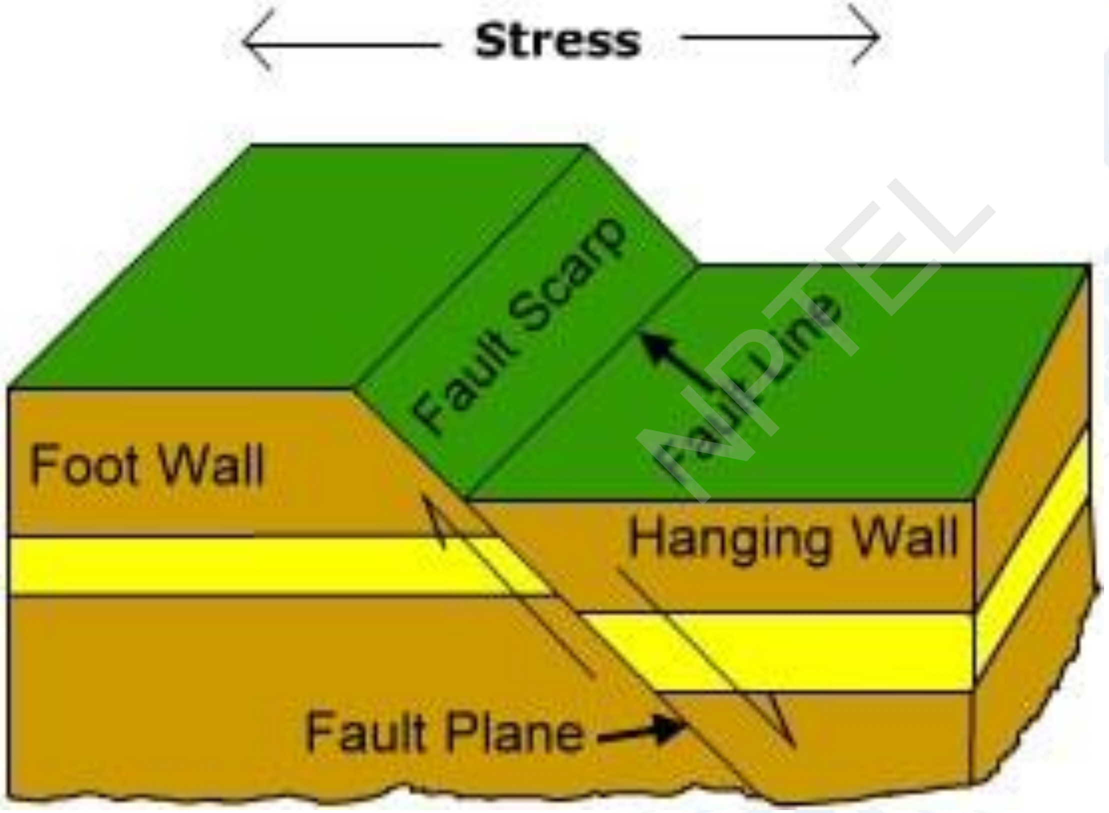
Figure 4.2-1: Fault scarp near Crowley Lake, California.



Focal Mechanisms: Fault Geometry

Focal Mechanisms: Fault Geometry

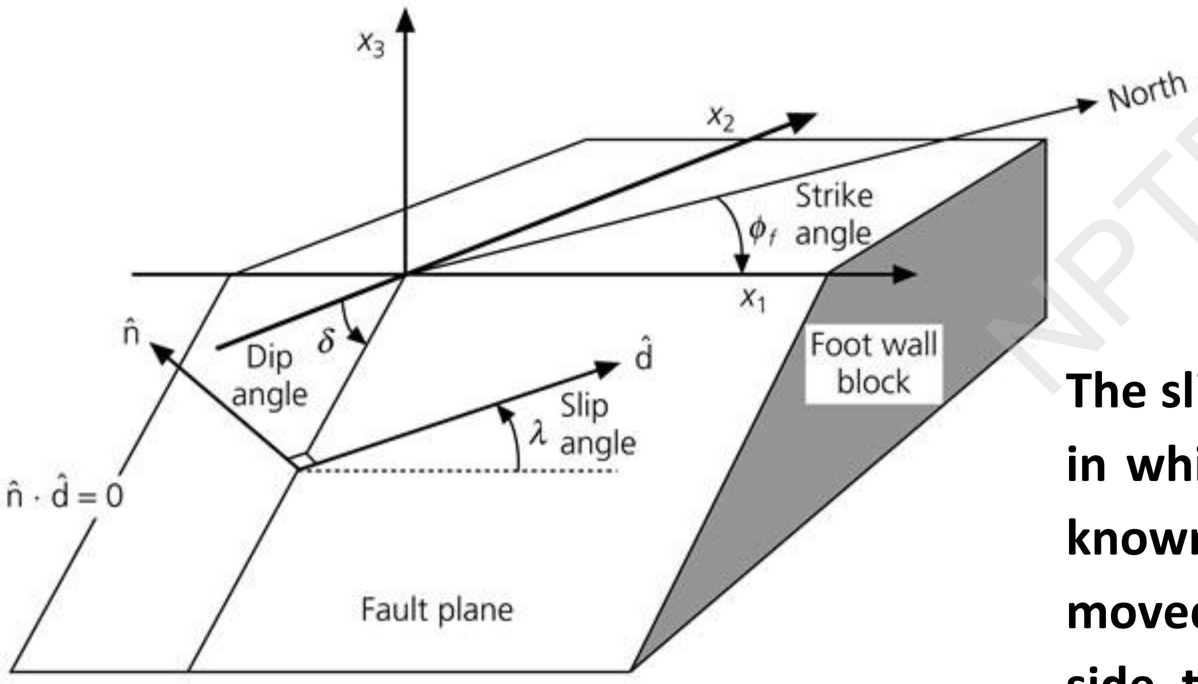
- **Thus the fault geometry is described in terms of the orientation of the fault plane and the direction of slip along the plane.**



Focal Mechanisms: **Fault Geometry**

- **Thus the fault geometry is described in terms of the orientation of the fault plane and the direction of slip along the plane.**

Figure 4.2-2: Fault geometry used in earthquake studies.

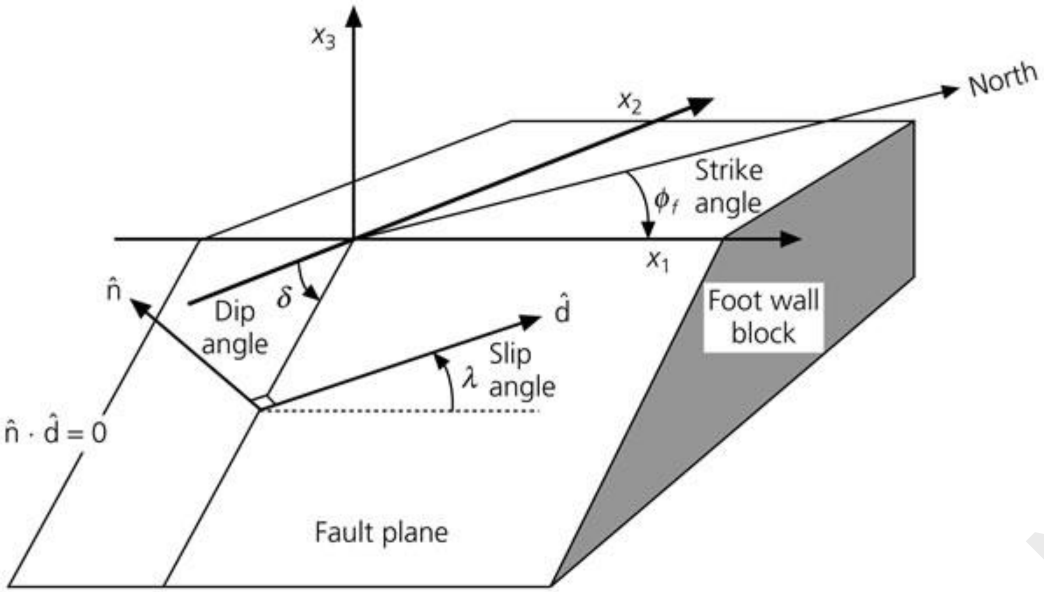


The fault plane is characterized by $\hat{n}$, its normal vector. The direction of motion is given by $\hat{d}$, the slip vector in the fault plane.

The slip vector indicates the direction in which the upper side of the fault, known as the hanging wall block, moved with respect to the lower side, the foot wall block.

Focal Mechanisms: Fault Geometry

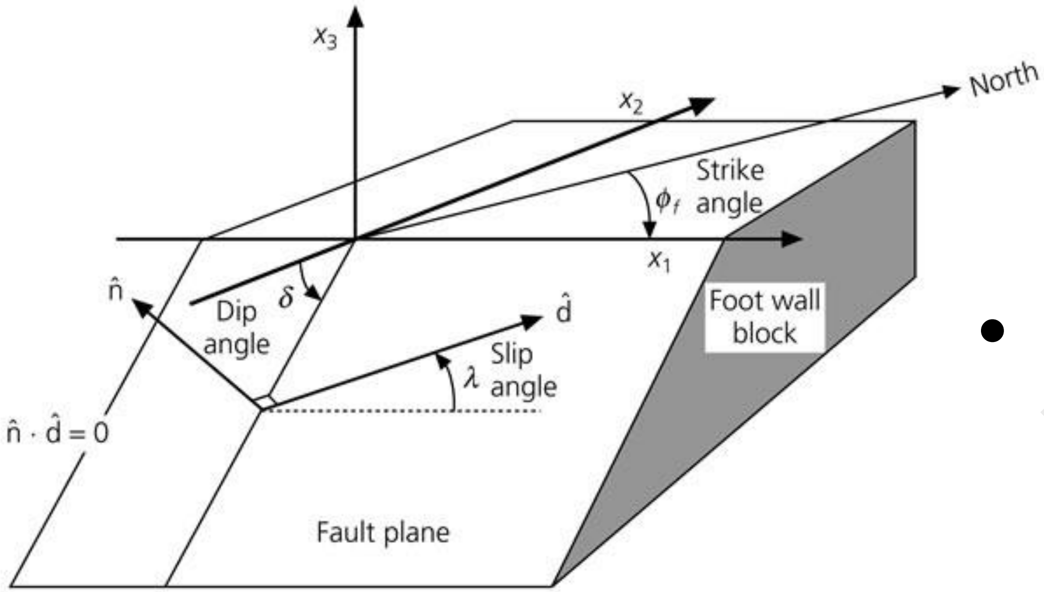
Figure 4.2-2: Fault geometry used in earthquake studies.



- **The x_1 axis is in the fault strike direction, the intersection of the fault plane with the earth's surface.**
- **The x_3 axis points upward, and the x_2 axis is perpendicular to the other two.**
- **The dip angle δ gives the orientation of the fault plane with respect to the surface.**
- **Because the x_1 axis could be defined in two directions, 180° apart, it is chosen so that the dip measured from the $-x_2$ axis is less than 90°.**

Focal Mechanisms: **Fault Geometry**

Figure 4.2-2: Fault geometry used in earthquake studies.



- **The direction of motion is represented by the slip angle, λ, measured counterclockwise in the fault plane from the x_1 direction, which gives the motion of the hanging wall block with respect to the foot wall block.**

- **The fault strike ϕ_f is defined as the angle in the plane of the earth's surface measured clockwise from north to the x_1 axis.**

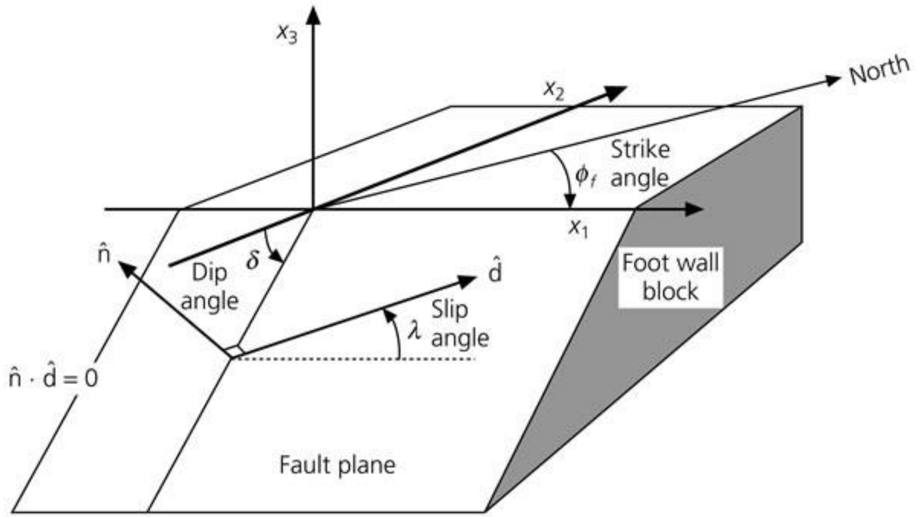
Focal Mechanisms: Fault Geometry

Alternatively, in geographic coordinate system, the orientation of the fault and slip can be described by giving the normal and slip vectors with $\hat{x}$ in north $\hat{y}$ in the west and $\hat{z}$ pointing up.

- Unit normal vector to the fault plane is

$$\hat{n} = \begin{pmatrix} -\sin\delta\sin\phi_f \\ \sin\delta\cos\phi_f \\ \cos\delta \end{pmatrix}$$

Figure 4.2-2: Fault geometry used in earthquake studies.



- Slip vector, a unit vector in the slip direction, is

$$\hat{d} = \begin{pmatrix} \cos\lambda\cos\phi_f + \sin\lambda\cos\delta\sin\phi_f \\ -\cos\lambda\sin\phi_f + \sin\lambda\cos\delta\cos\phi_f \\ \sin\lambda\sin\delta \end{pmatrix}$$

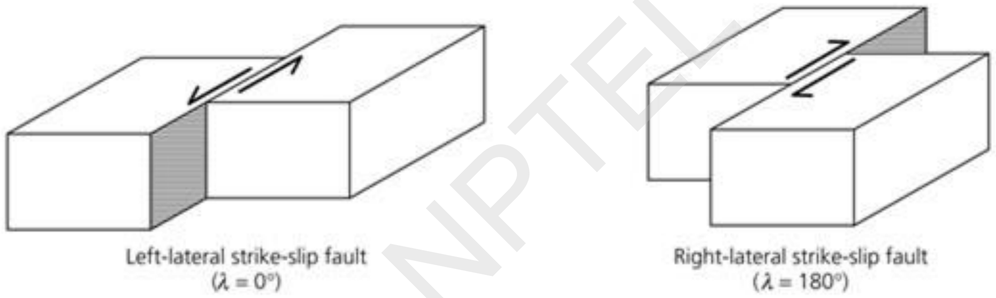
Focal Mechanisms: Classification of Faults based on Fault Geometry

These two different coordinate systems, (ϕ_f, δ, λ) and, $\left(\widehat{n},\ \hat{d}\right)$ are useful for different purposes.

Some calculations are more easily done with respect to the fault, whereas others are more easily done with respect to geographic directions.

Pure strike-slip

Figure 4.2-3: Basic types of faulting.

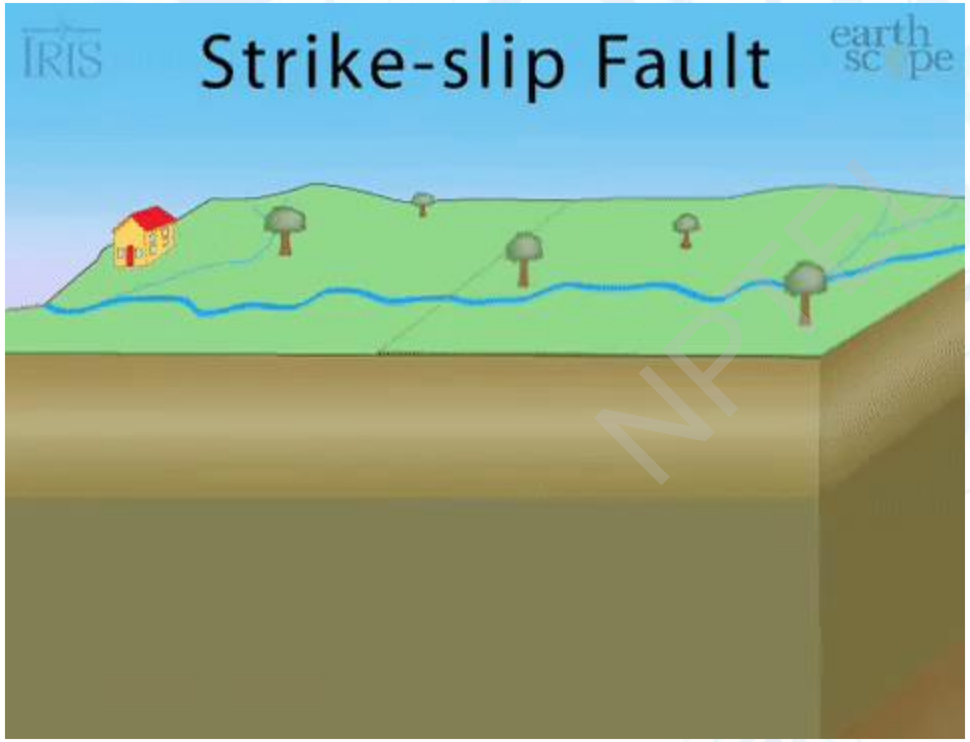


When λ = 0°, the hanging wall moves to the right, and the motion is called left-lateral.

Similarly, for λ = 180°, right-lateral motion occurs.

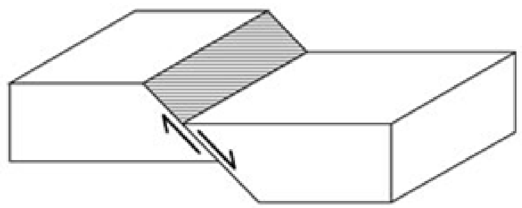
Focal Mechanisms: Classification of Faults based on Fault Geometry

Pure strike-slip

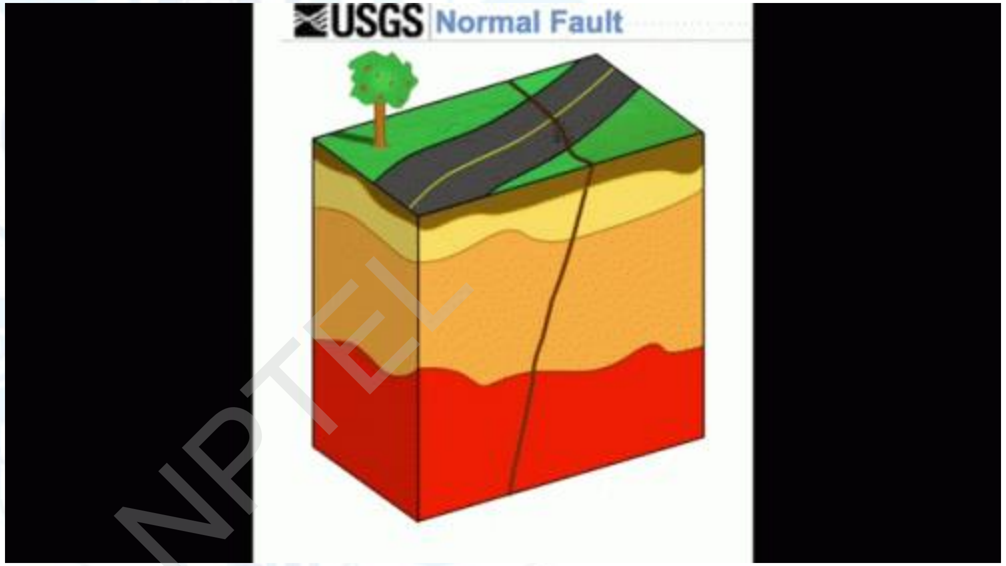


Focal Mechanisms: Classification of Faults based on Fault Geometry

Pure dip-slip



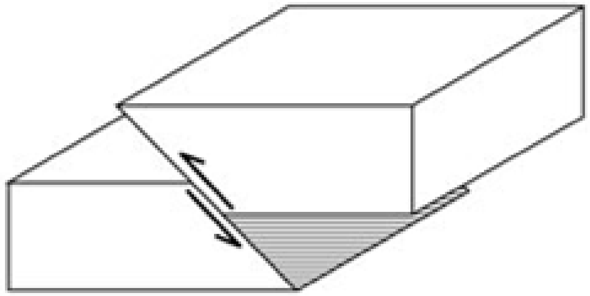
Normal dip-slip fault
($\lambda = -90°$)



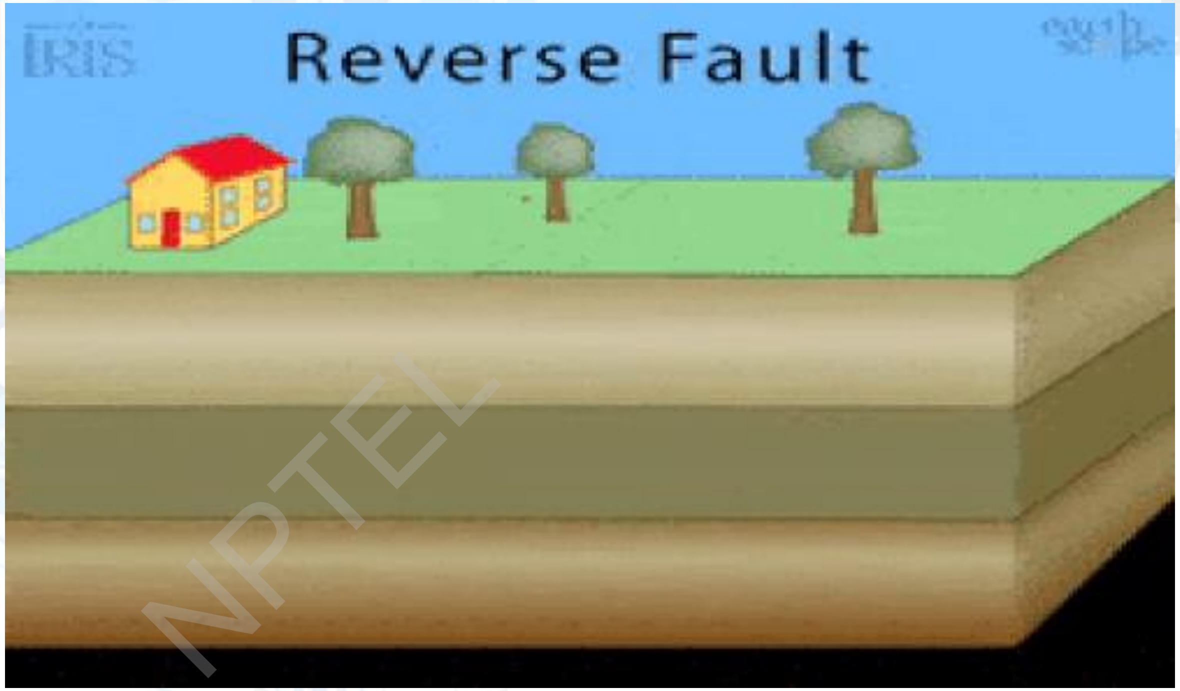
When λ = 270°, the hanging wall slides downward, causing normal faulting.

Focal Mechanisms: Classification of Faults based on Fault Geometry

Pure dip-slip



Reverse dip-slip fault
($\lambda = 90°$)



In the opposite case, λ = 90°, and the hanging wall goes upward, yielding reverse, or thrust, faulting.

Focal Mechanisms: Points to remember!

- Most earthquakes consist of some combination of these motions and have slip angles between these values.
- It is thus useful, when thinking about earthquake mechanisms, to remember the three basic faults.
- If we treat a fault as rectangular, the dimension along the strike is called the fault length, and the dimension in the dip direction is known as the fault width.
- The fault may curve and require a three-dimensional description.
- Rupture may occur over a long time and consist of several sub-events on different parts of the fault with different orientations.
- Such complicated seismic events, however, can be treated as a superposition of simple events.

Summary

- Elastic rebound theory states that strain accumulated in the rock is more than the rocks on the fault can withstand, and the fault slips, resulting in an earthquake.

- **Interseismic stage** consists of long periods between large earthquakes during which elastic strain accumulation occurs in the broad region.

- **Preseismic stage** that can be associated with small earthquakes (foreshocks).

- Earthquake itself marks the **coseismic phase** during which rapid motion on the fault occur and generate seismic waves.
- **Postseismic phase** occurs after the earthquake, and aftershocks and transient afterslip occur for a period of years.

- The two different coordinate systems, (ϕ_f, δ, λ) and ($\hat{n}$, $\hat{d}$), are useful to describe the fault geometry.

Summary

- Unit normal vector to the fault plane is $$\hat{n} = \begin{pmatrix} -\sin\delta\sin\phi_f \\ \sin\delta\cos\phi_f \\ \cos\delta \end{pmatrix}$$

- Slip vector, a unit vector in the slip direction, is $$\hat{d} = \begin{pmatrix} \cos\lambda\cos\phi_f + \sin\lambda\cos\delta\sin\phi_f \\ -\cos\lambda\sin\phi_f + \sin\lambda\cos\delta\cos\phi_f \\ \sin\lambda\sin\delta \end{pmatrix}$$

- For pure strike-slip fault λ = 0°, the hanging wall moves to the right, and the motion is called left-lateral and for λ = 180°, right-lateral motion occurs.

- For pure dip-slip fault λ = 270°, the hanging wall slides downward, causing normal faulting and λ = 90°, and the hanging wall goes upward, yielding reverse, or thrust, faulting.

REFERENCES

- **Stein, Seth, and Michael Wysession. An introduction to seismology, earthquakes, and earth structure. John Wiley & Sons, 2009.**
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- **Kearey, Philip, Michael Brooks, and Ian Hill. An introduction to geophysical exploration. Vol. 4. John Wiley & Sons, 2002.**
- **https://geologyscience.com/geology-branches/structural-geology/stress-and-strain/**
- **Seismology course, Professor Derek Schutt, Colorado State Univ., USA.**

THANK YOU !