Chapter 15

Structures

Plummer/McGeary/Carlson

TECTONIC FORCES AT WORK

- Stress & Strain
  - Stress
  - Strain
  - Compressive stress

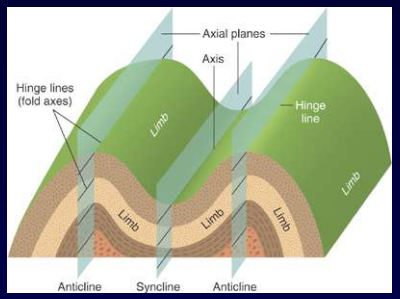
    Shortening strain
  - Tensional stress

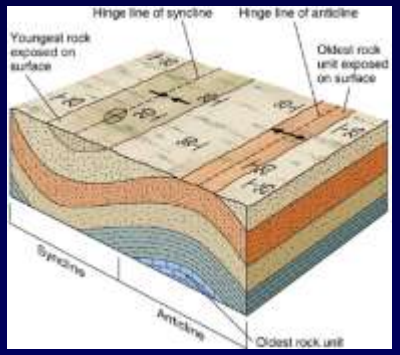
    stretching or extensional strain
  - Shear Stress

    Shear strain

Types of Geologic Structures

- ***Folds*** are wavelike bends in layered rock
  - Represent rock strained in a *ductile* manner, usually under *compression*
- The ***axial plane*** divides a fold into its two *limbs*
  - The surface trace of an axial plane is called the ***hinge line*** **(or *axis*)** of the fold
- *Anticlines* are upward-arching folds, and *Synclines* are downward-arching folds





Faults, Folds, and Rock Deformation — Geologic Structure

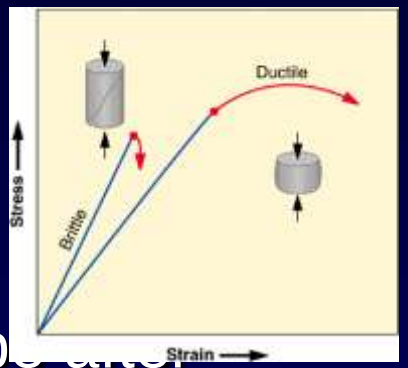
- Deformation of rocks over large volumes
  - Rocks break (fault) and flow (fold) in many settings
  - What drives deformation? — tectonics and gravity
  - Stress regimes: compression, tension, shear
  - Why do we care? — geologic history and applications
  - Compare and contrast metamorphic processes
- Attitudes of rocks; geologic maps and cross sections
- Types of structures: varieties of folds and faults
  - Styles reflect local to regional stress regimes

Behavior of rocks to stress & strain

- Elastic
  - Elastic limit
- Plastic
- Brittle

Rock Responses to Stress and Strain

- Rocks behave as ***elastic***, ***ductile*** **or** ***brittle*** materials depending on:
  - amount and rate of stress application
  - type of rock
  - temperature and pressure
- If deformed materials return to original shape after stress removal, they are behaving ***elastically***
- However, once the stress exceeds the ***elastic limit*** of a rock, it deforms permanently
  - ***ductile*** deformation involves bending ***plastically***
  - ***brittle*** deformation involves ***fracturing***



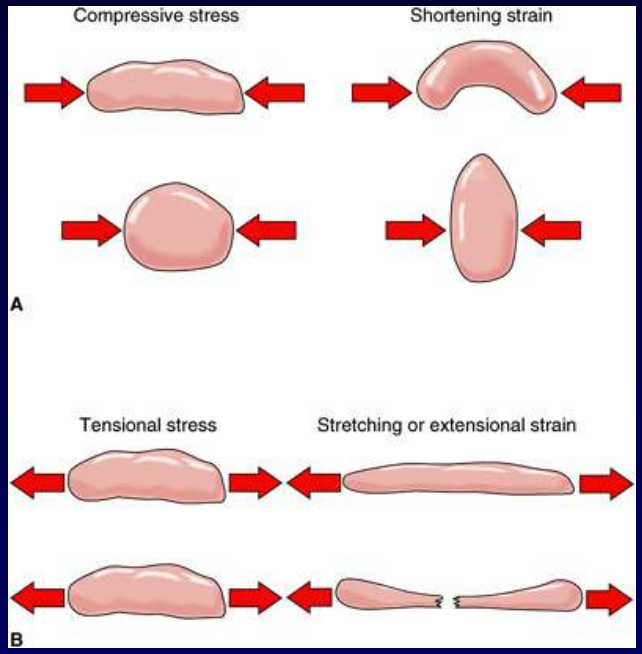
Geologic Structures

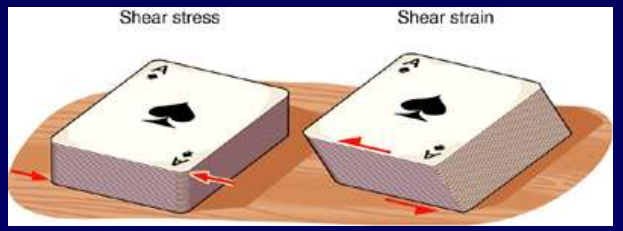
- ***Geologic structures*** are dynamically-produced patterns or arrangements of rock or sediment that result from, and give information about, forces within the Earth
  - Produced as rocks change shape and orientation in response to applied stress
  - ***Structural geology*** is the study of the shapes, arrangement, and interrelationships of bedrock units and the forces that cause them

Folded and Faulted Sedimentary Bedrock

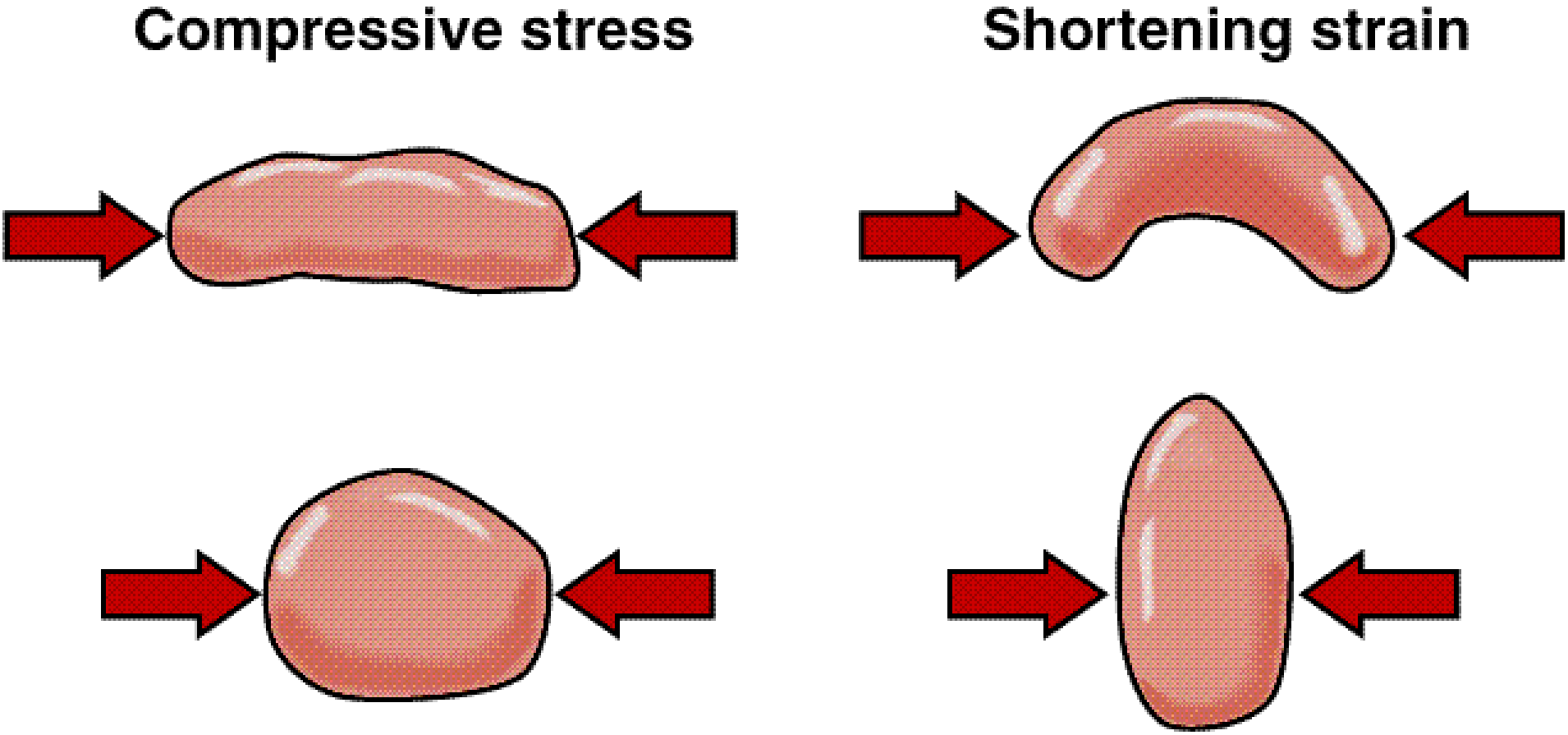
Stress and Strain

- ***Stress*** *is a force per unit area*
  - The three basic types of stress are ***compressive***, ***tensional*** **and** ***shear***
- ***Strain*** **is a change in size or shape in response to stress**
  - Structures produced are examples of strain that are indicative of the type of stress and its rate of application, as well the physical properties of the rock or sediment being stressed



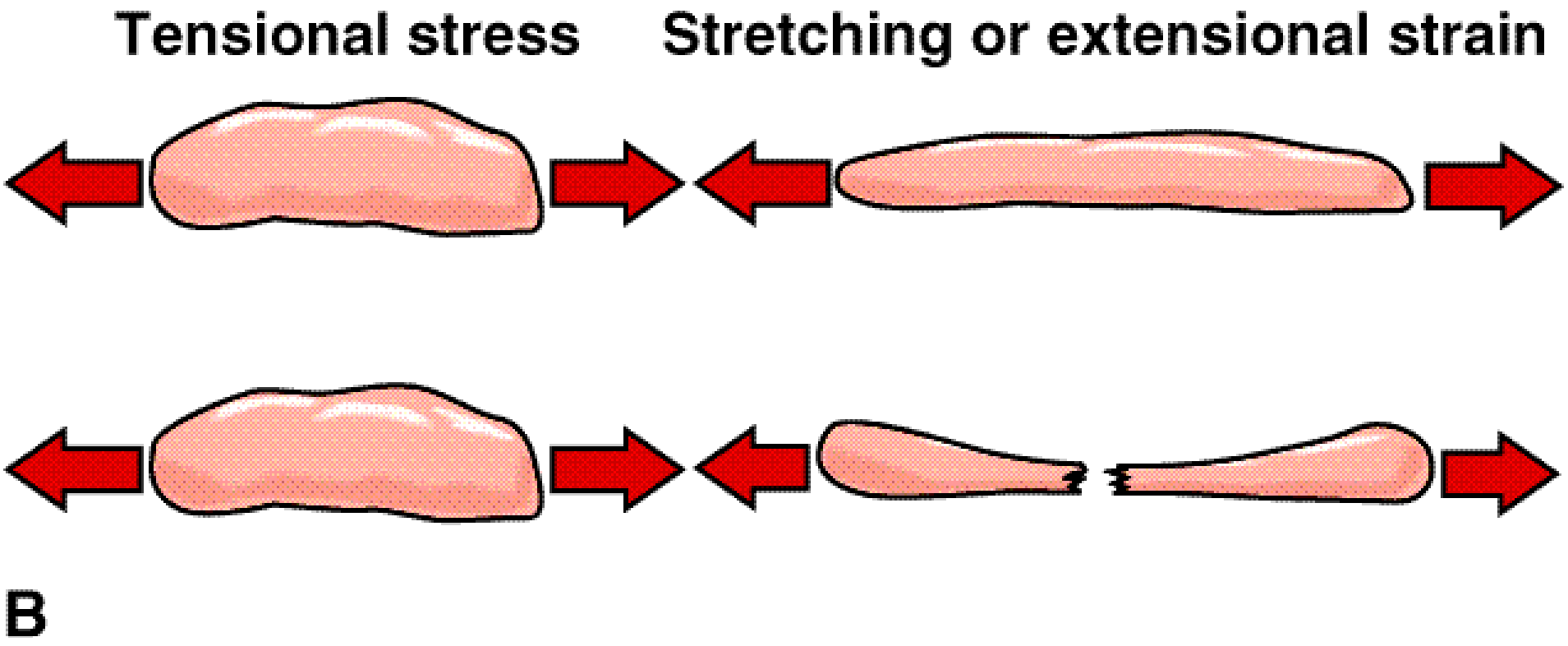


Compressive Stress



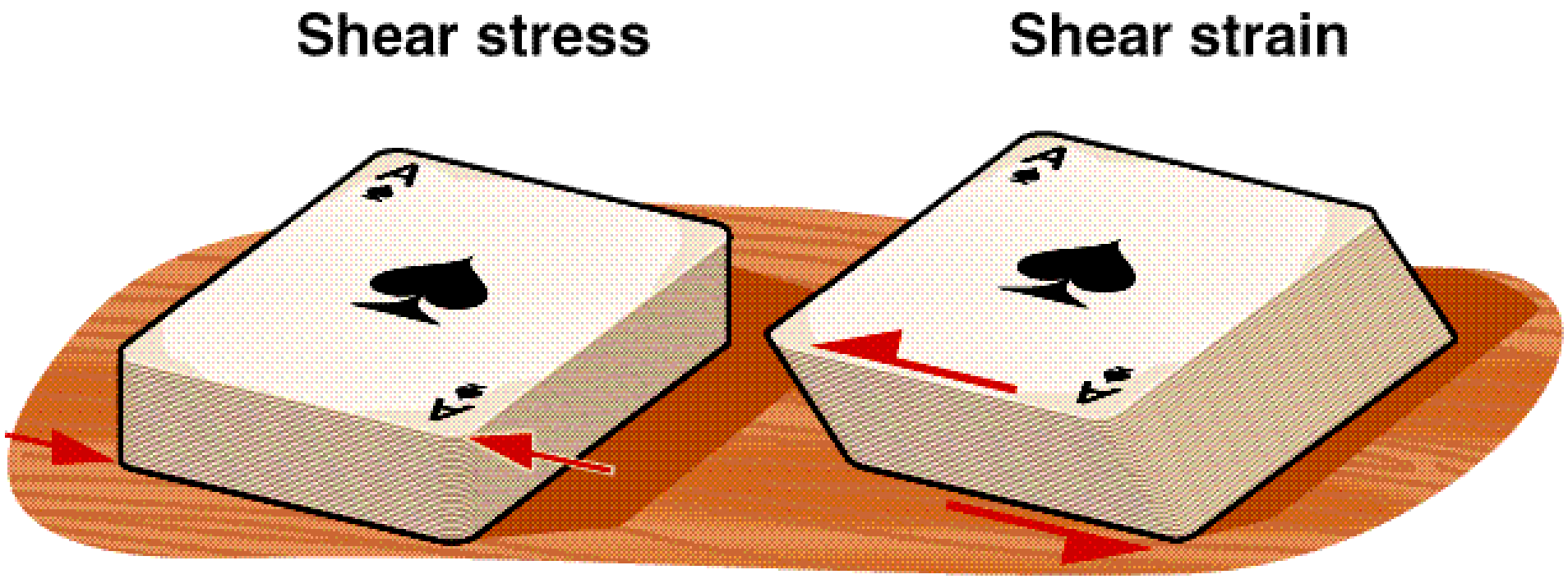
A

Tension Stress



B

Shear Stress



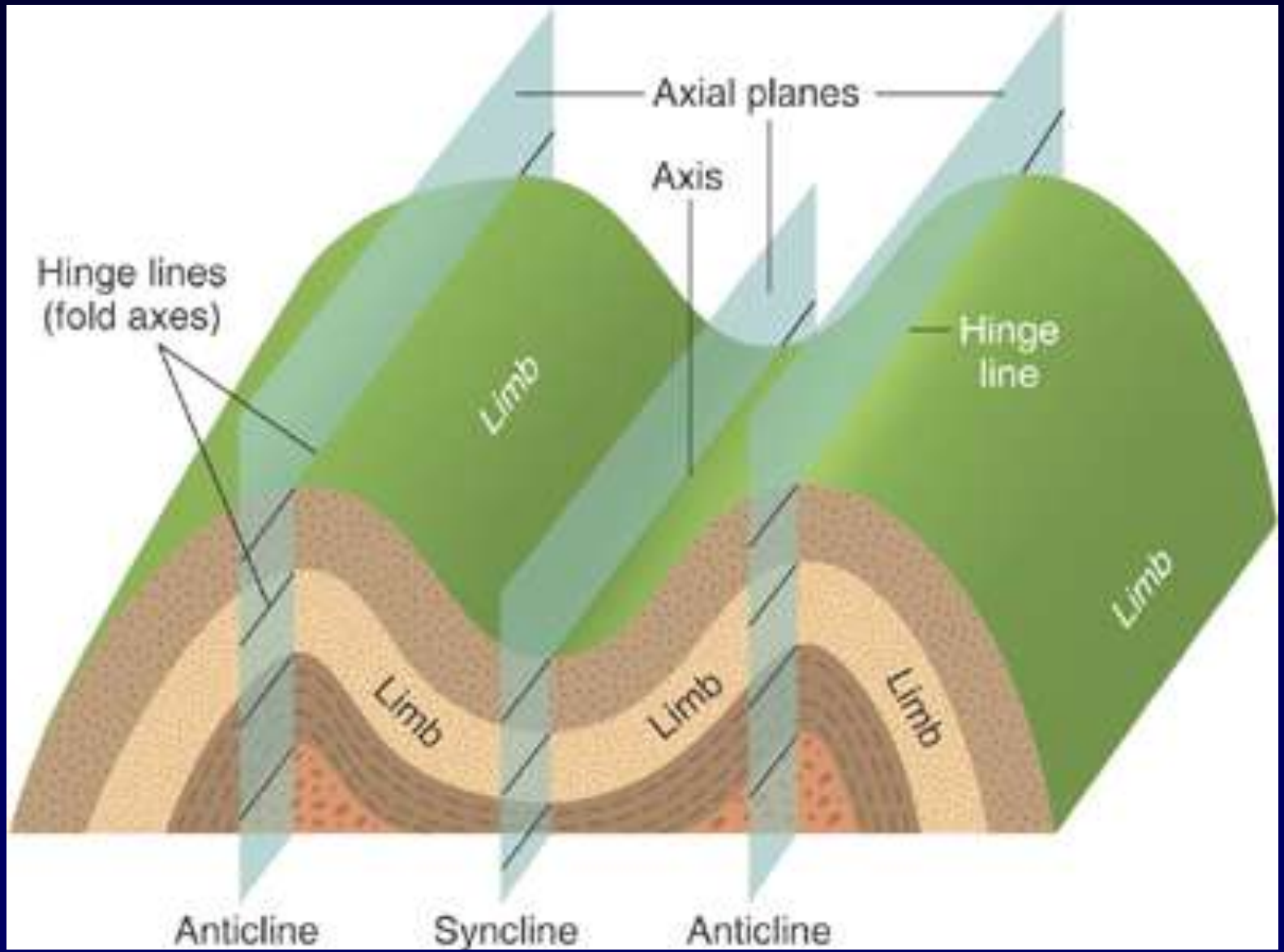
FOLDS

- Anticline vs. syncline
  - Hinge line (axis)
  - Limb
  - Axial plane
- Plunging fold
- Structural dome
- Structural basin

Folds

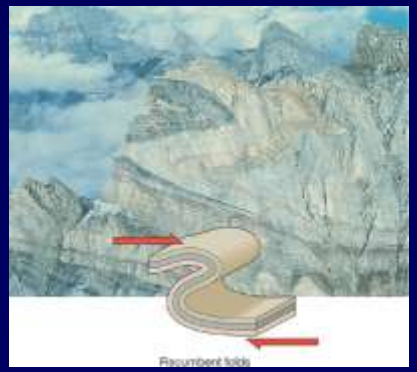
- Types defined by direction of dips
  - *Anticlines* (dip away)
  - *Synclines* (dip toward)
  - *Monoclines* (dip one way)
  - *Domes* (dip outward)
  - Structural *basins* (dip inward)
- Other descriptive terms, including fold axis, axial plane
- Folds can be symmetric, asymmetric, upright, overturned (attitude of the limbs)
- Folds can plunge (attitude of fold axis)

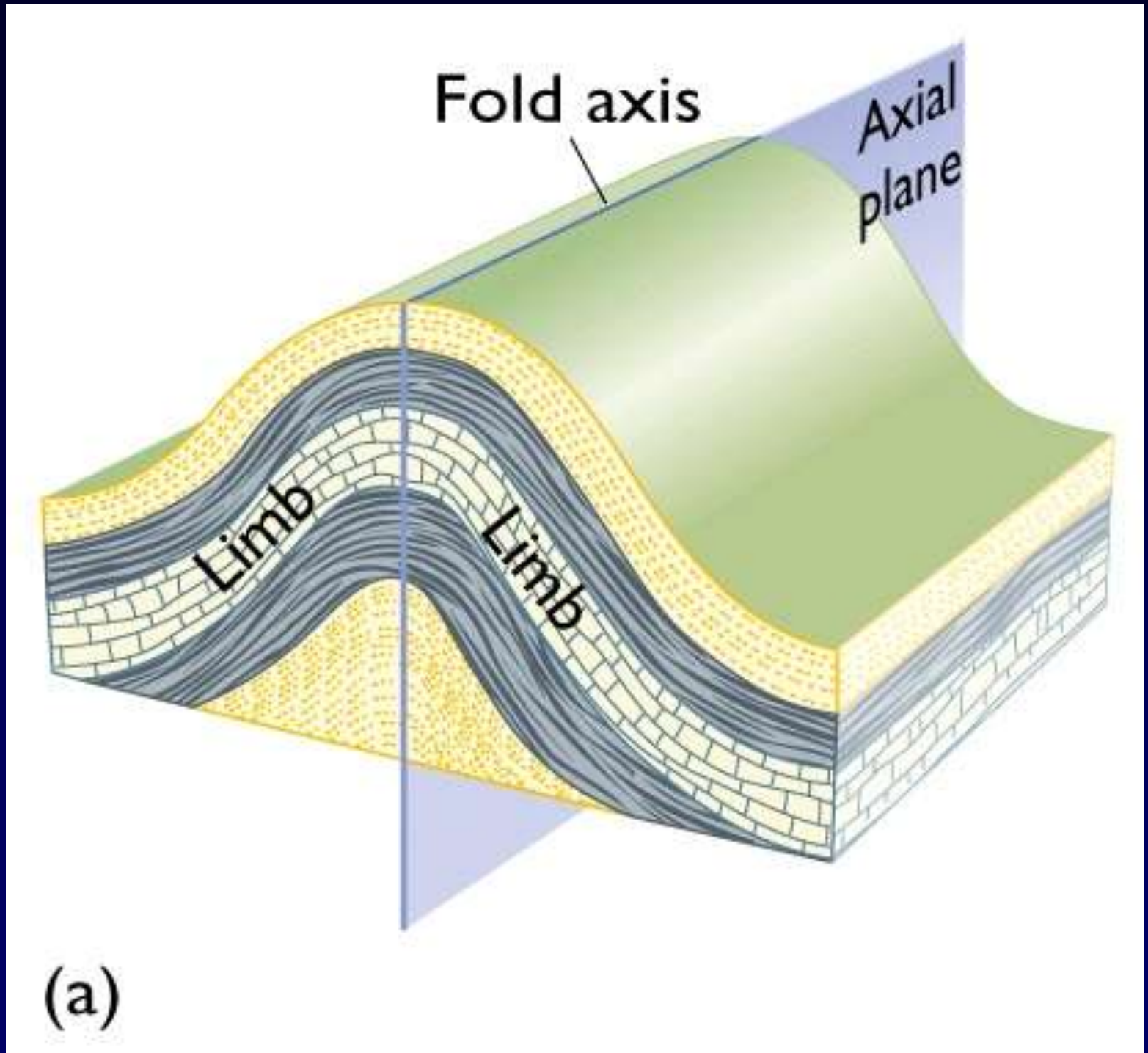
- The ***axial plane*** divides a fold into its two ***limbs***
  - The surface trace of an axial plane is called the ***hinge line*** **(or *axis*)** of the fold

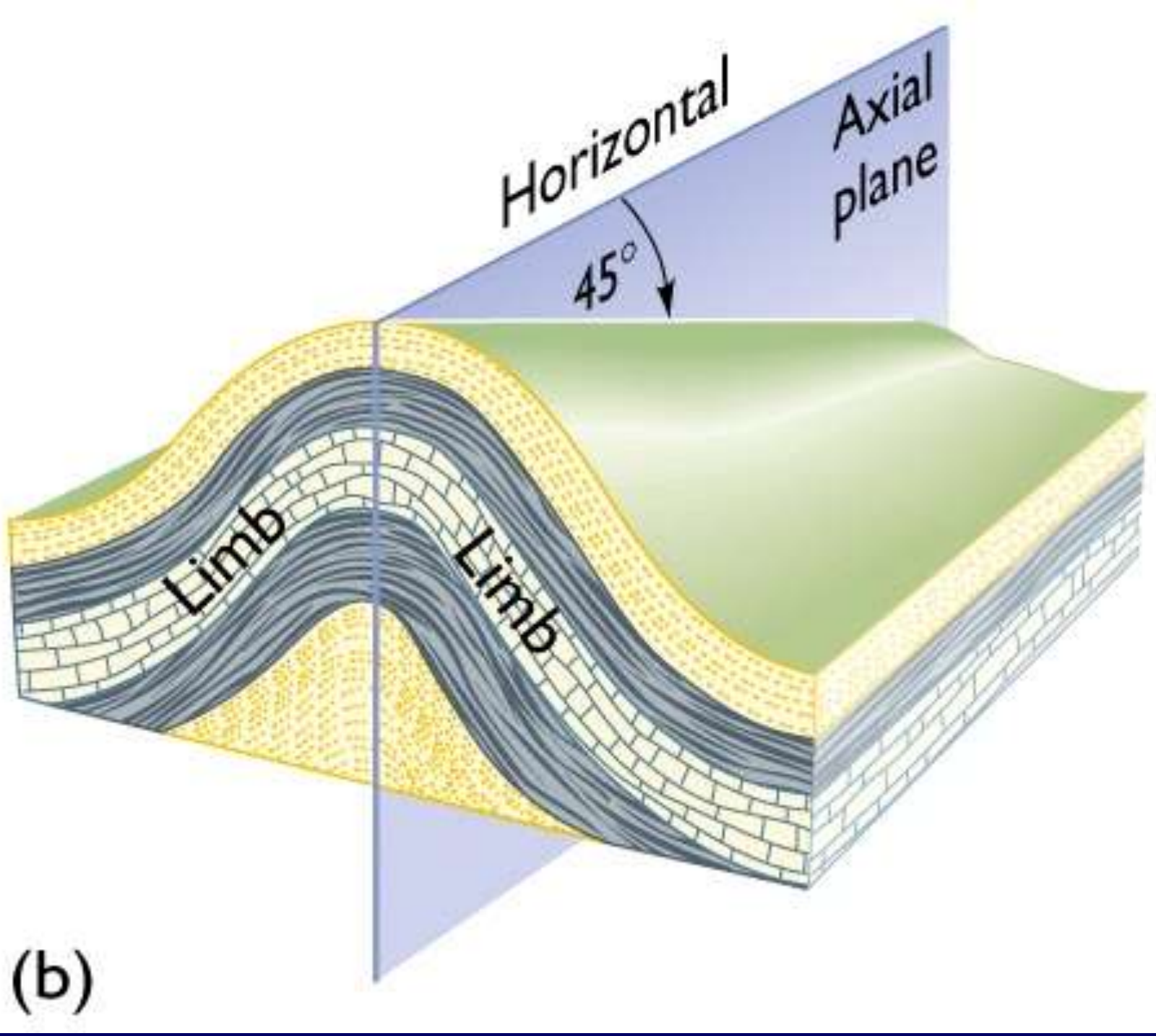


Types of Folds

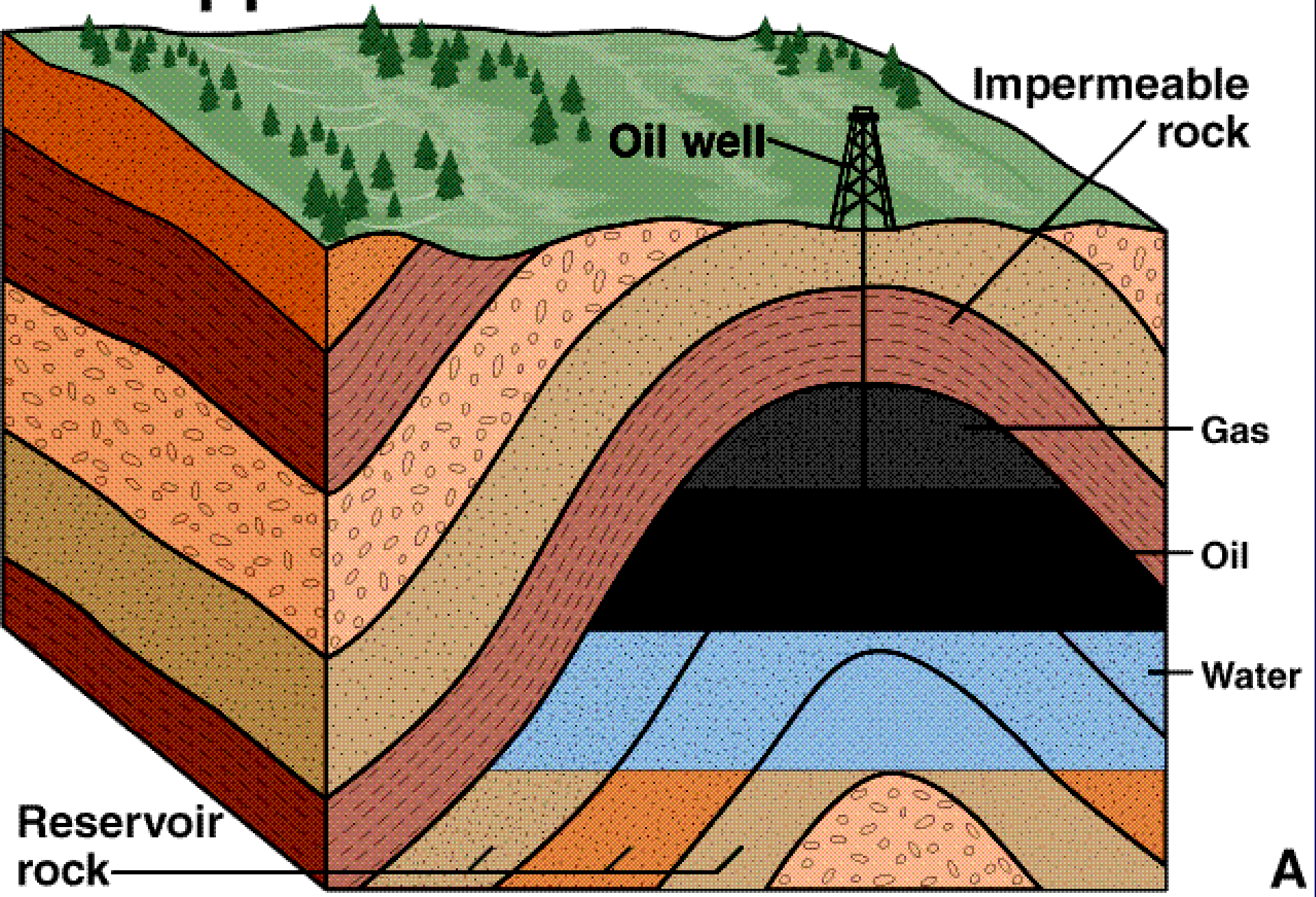
- ***Plunging folds*** are folds in which the hinge line is not horizontal
  - Where surfaces have been leveled by erosion, plunging folds form V- or horseshoe-shaped patterns of exposed rock layers (beds)
- ***Open folds*** have limbs that dip gently,
- whereas ***isoclinal folds*** have parallel limbs
- ***Overturned folds*** have limbs that dip in the same directions, and ***recumbent folds*** are overturned to the point of being horizontal



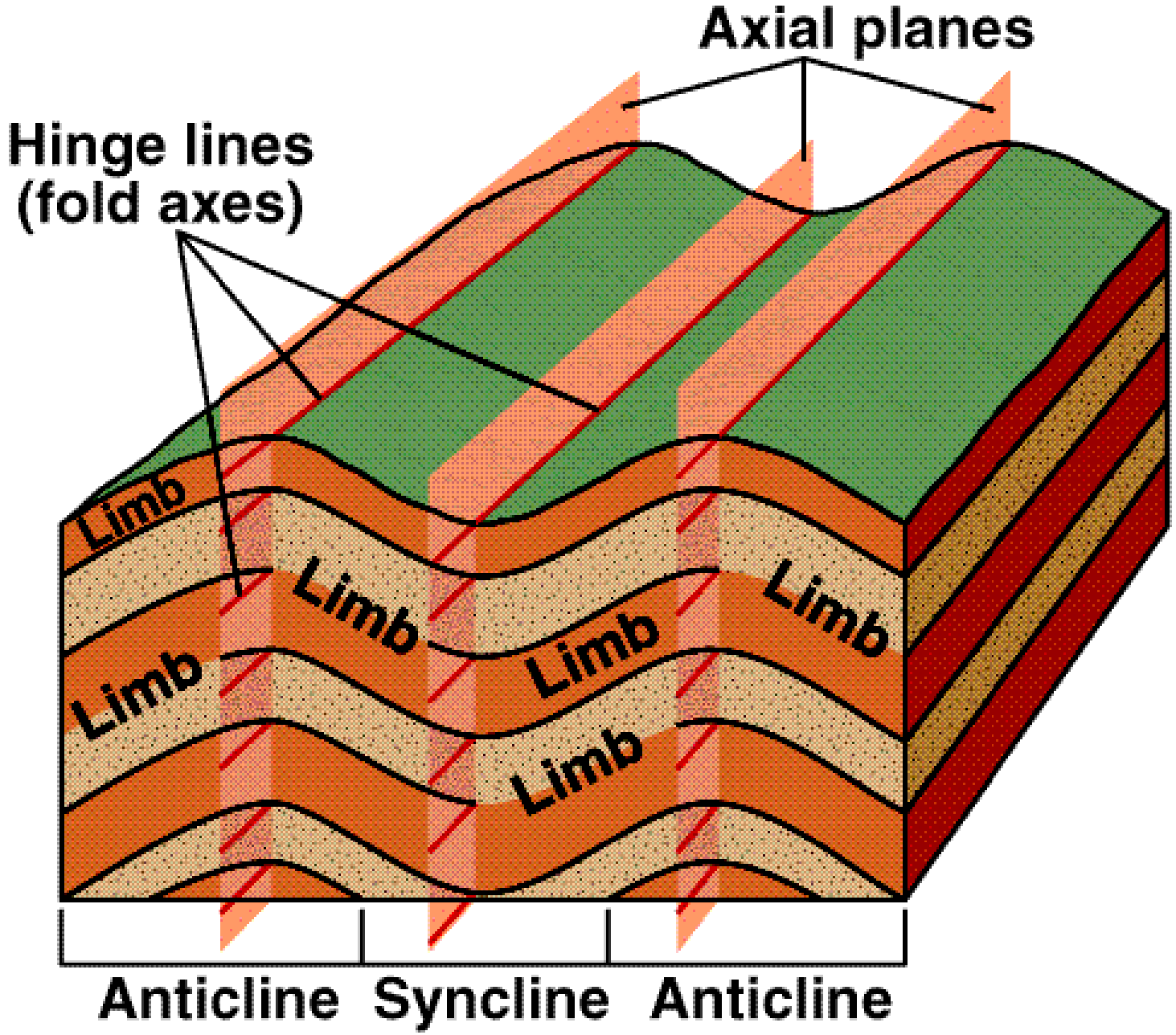

Fold axis
Axial plane
Limb
Limb
(a)

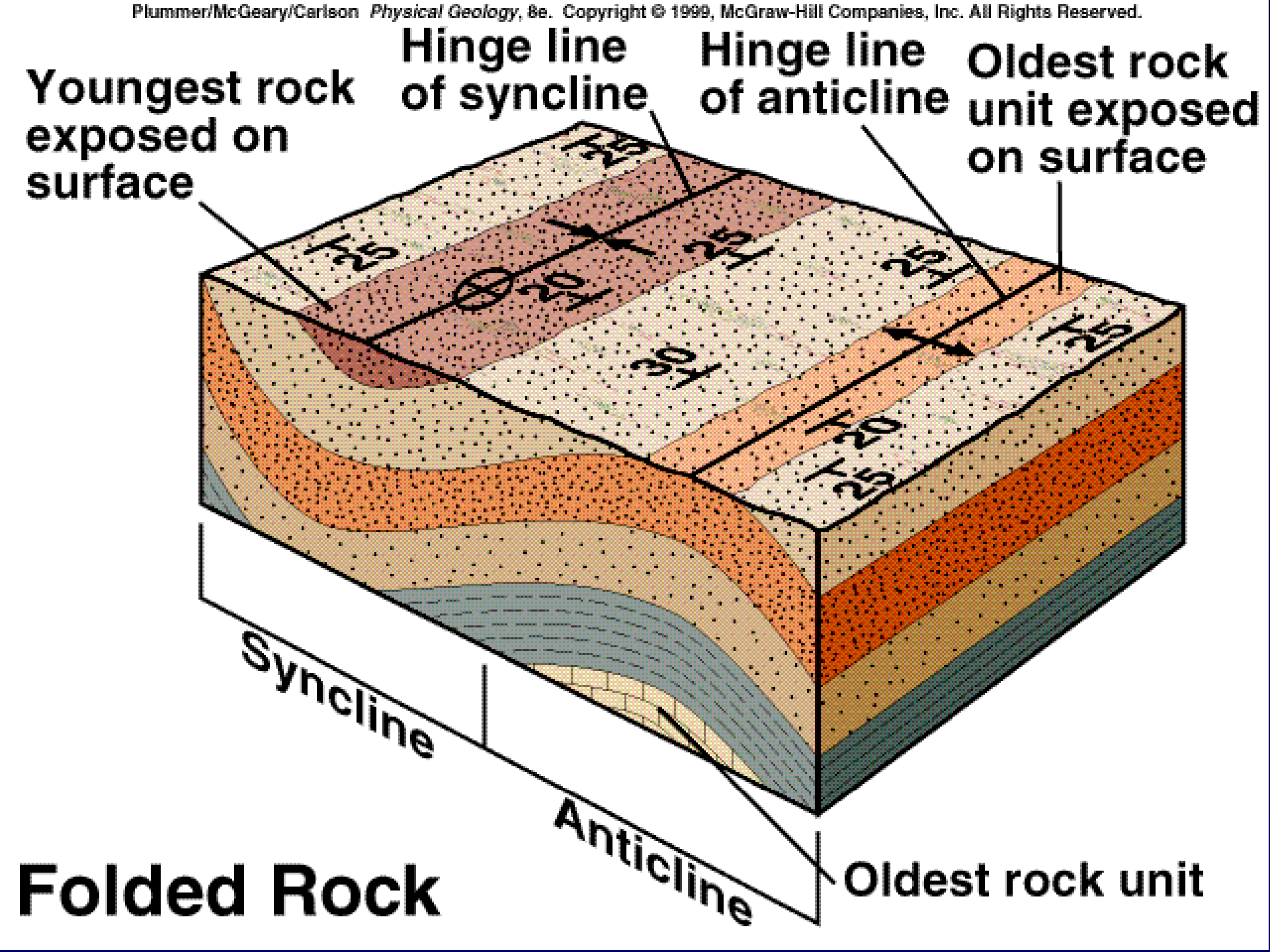

Horizontal
Axial plane
45°
Limb
Limb
(b)

Trapped Oil and Gas in Anticline



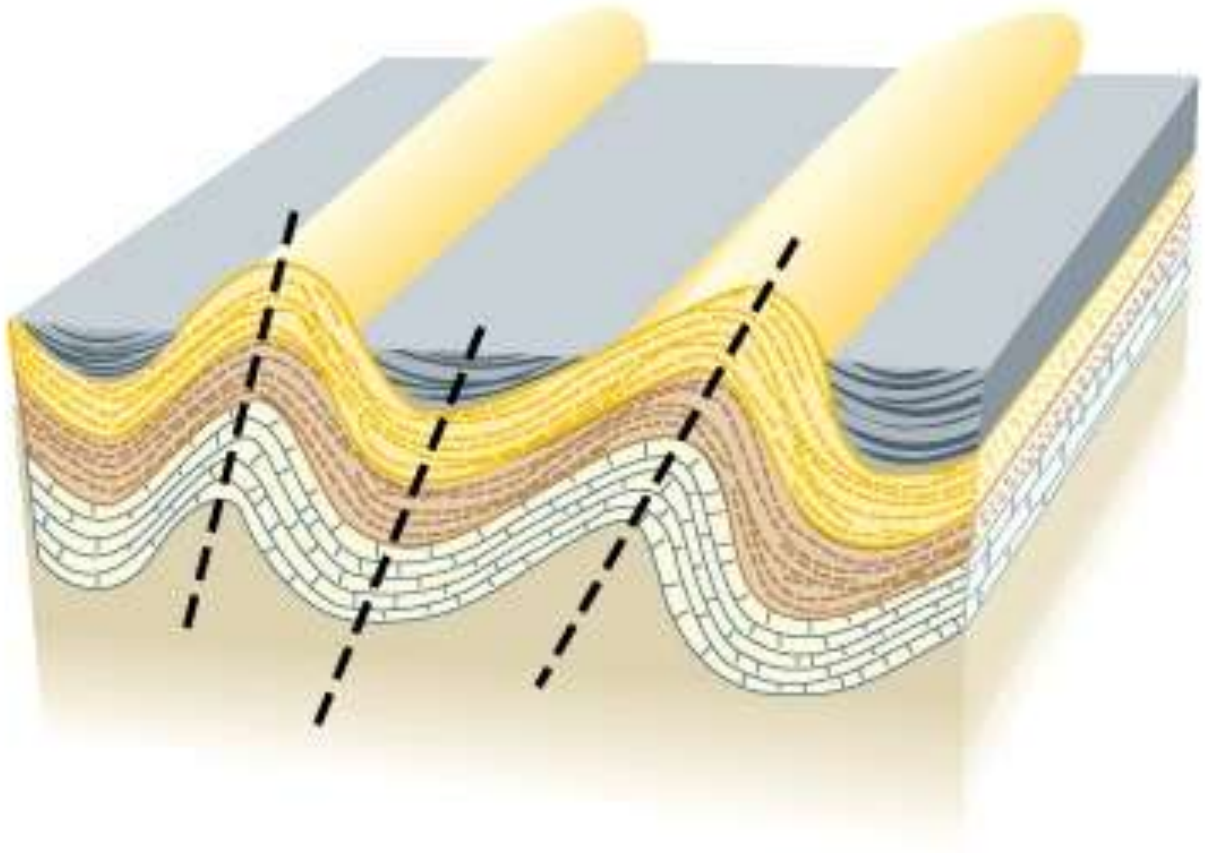
Two Anticlines and a Syncline



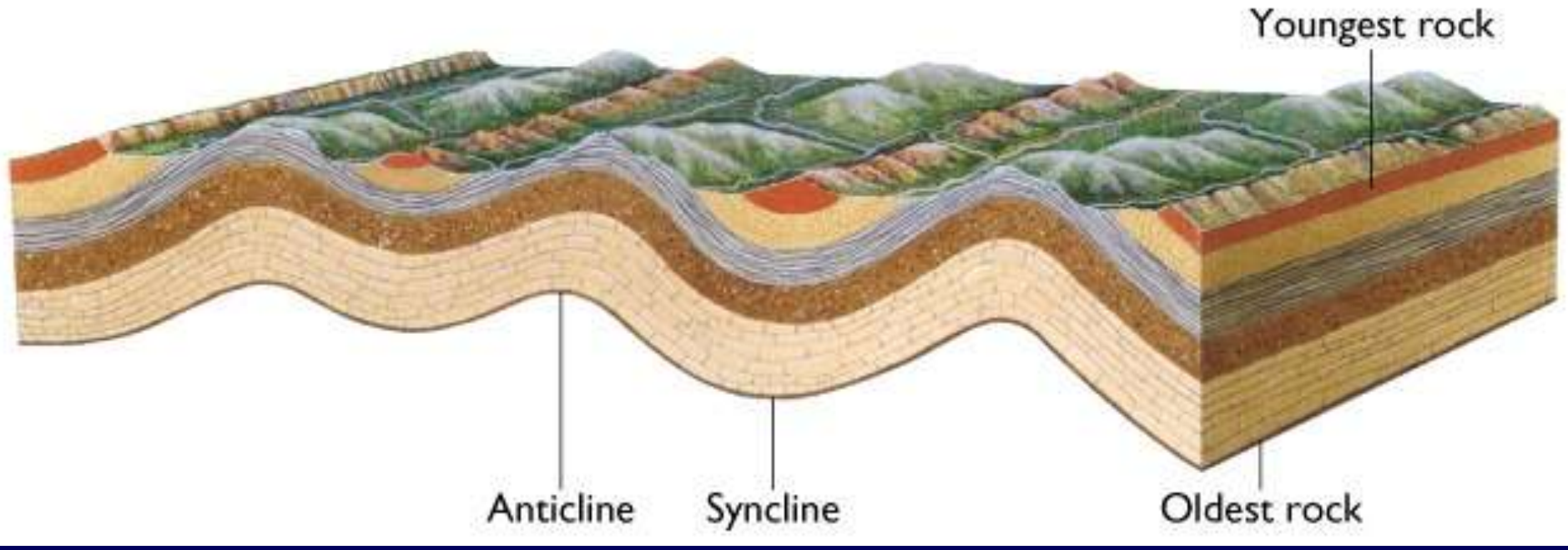


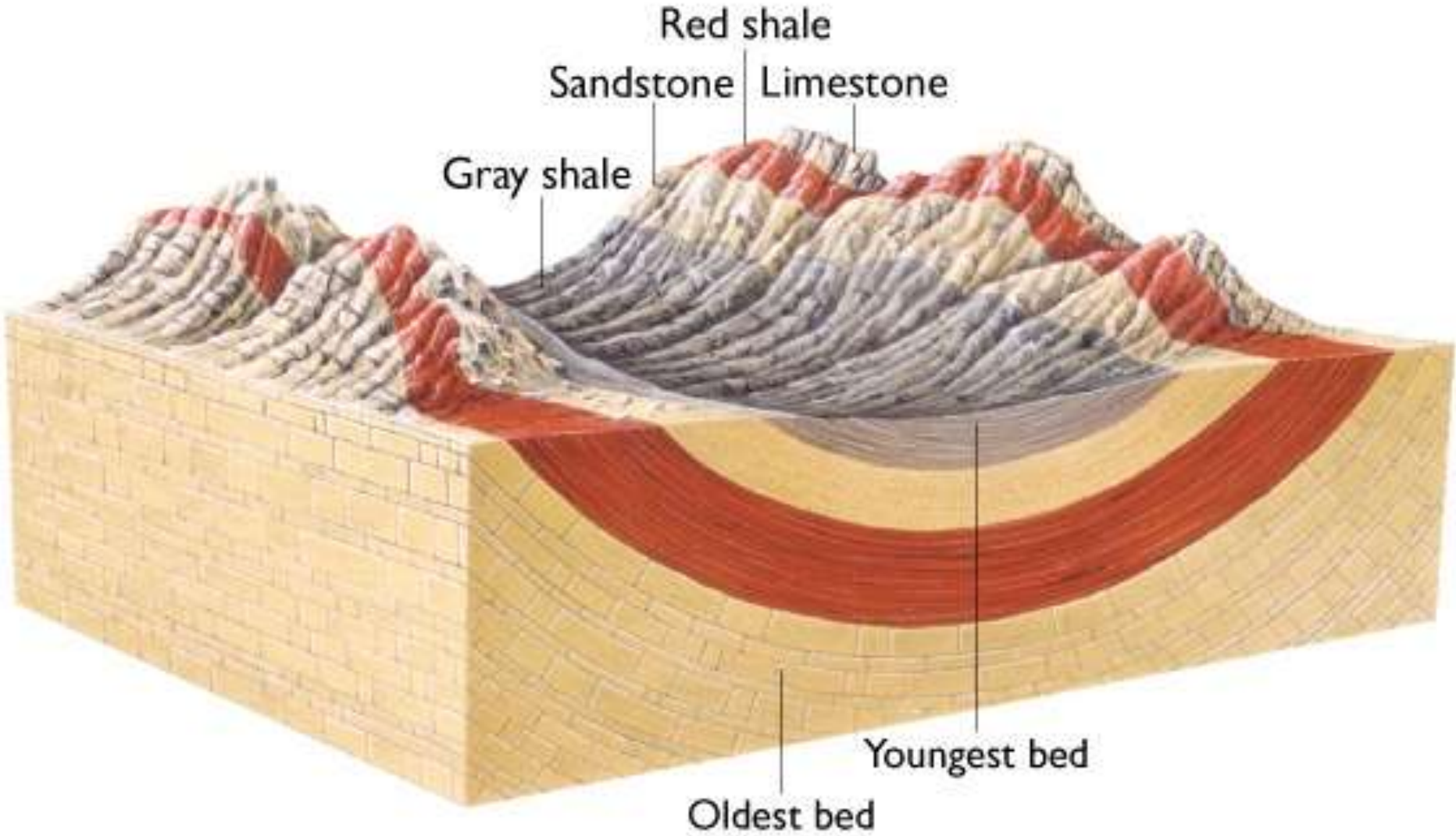
Folded Rock

(b) Asymmetrical folds



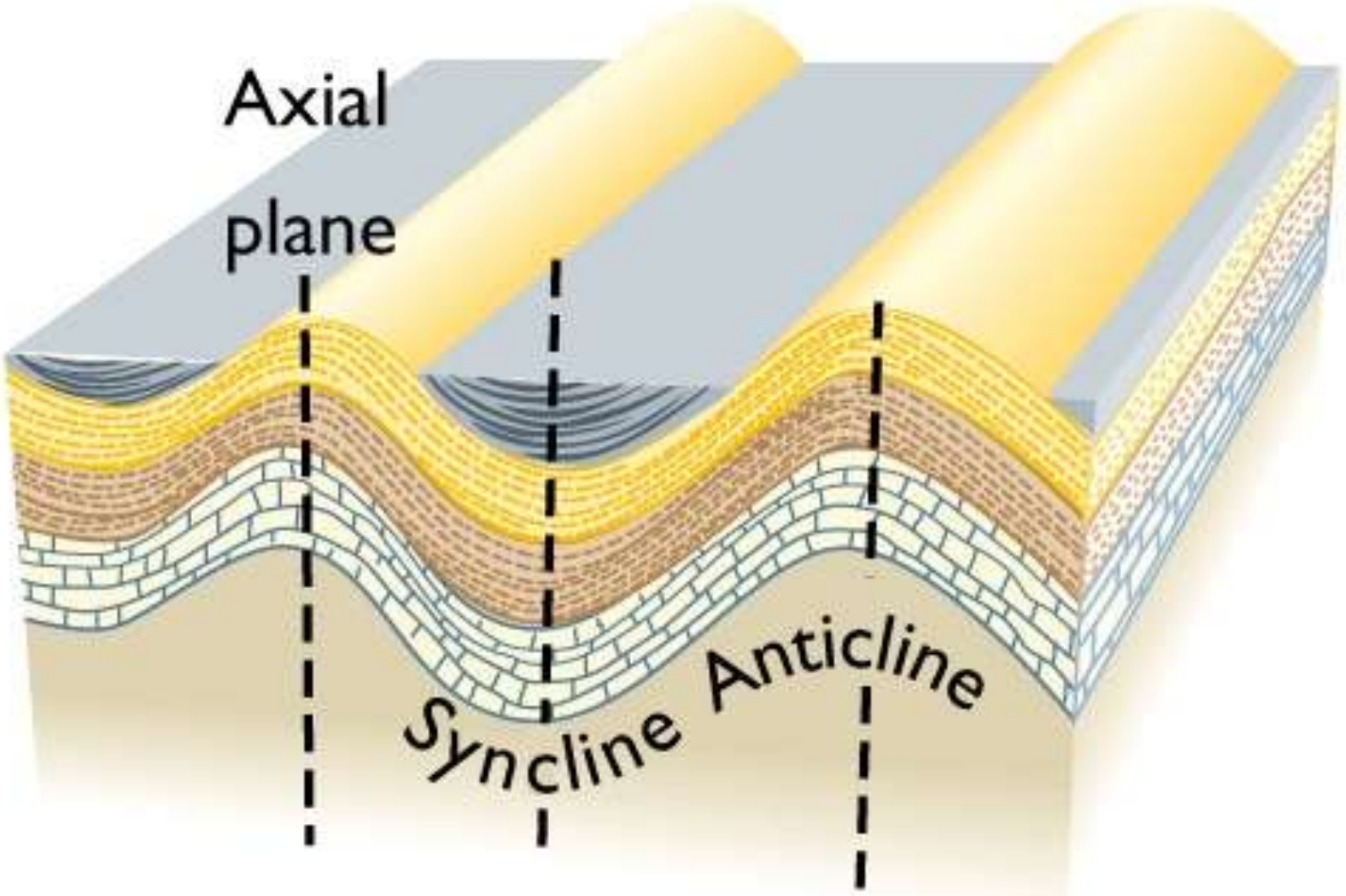
Beds in one limb dip more steeply than those in the others


Youngest rock
Anticline
Syncline
Oldest rock

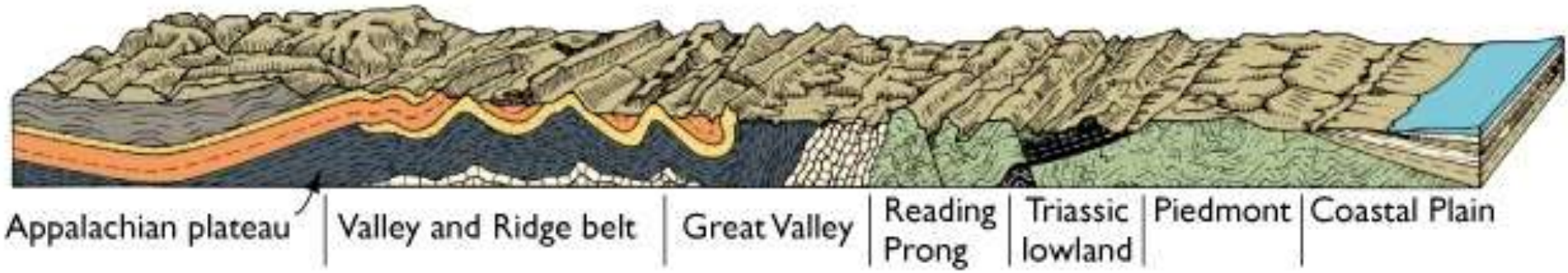

Red shale
Sandstone
Limestone
Gray shale
Youngest bed
Oldest bed

Folded Rock

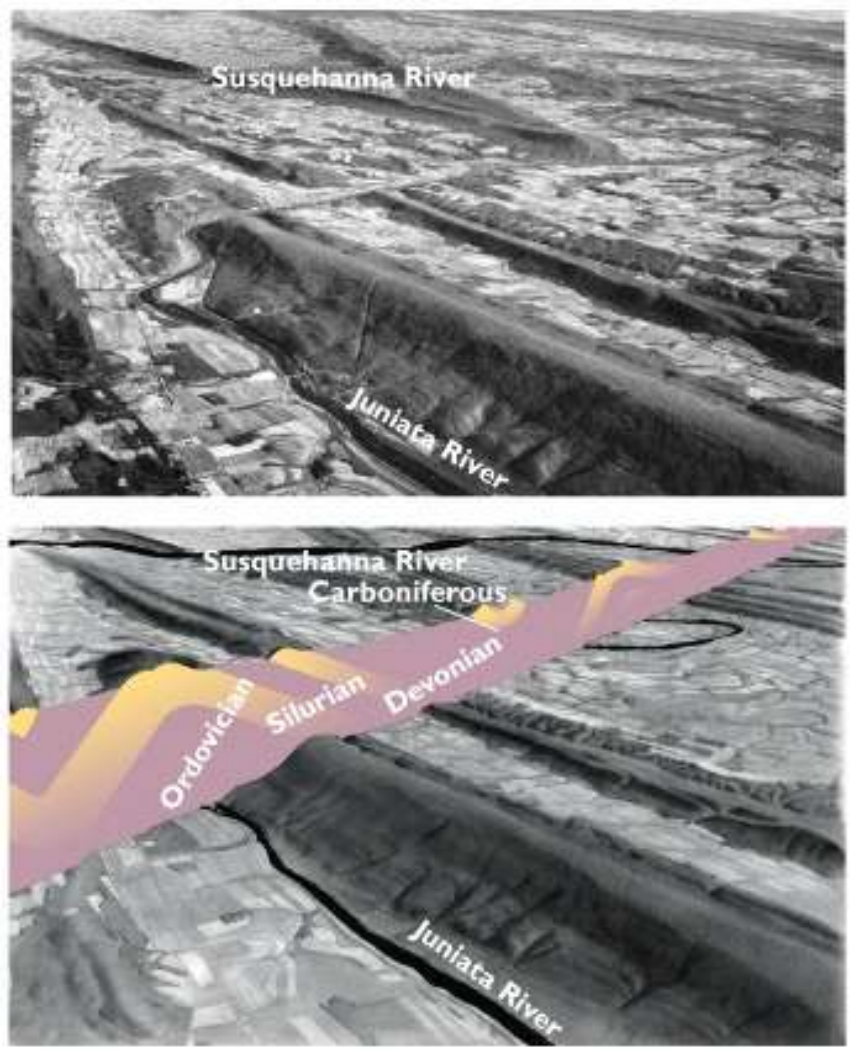
(a) Symmetrical folds

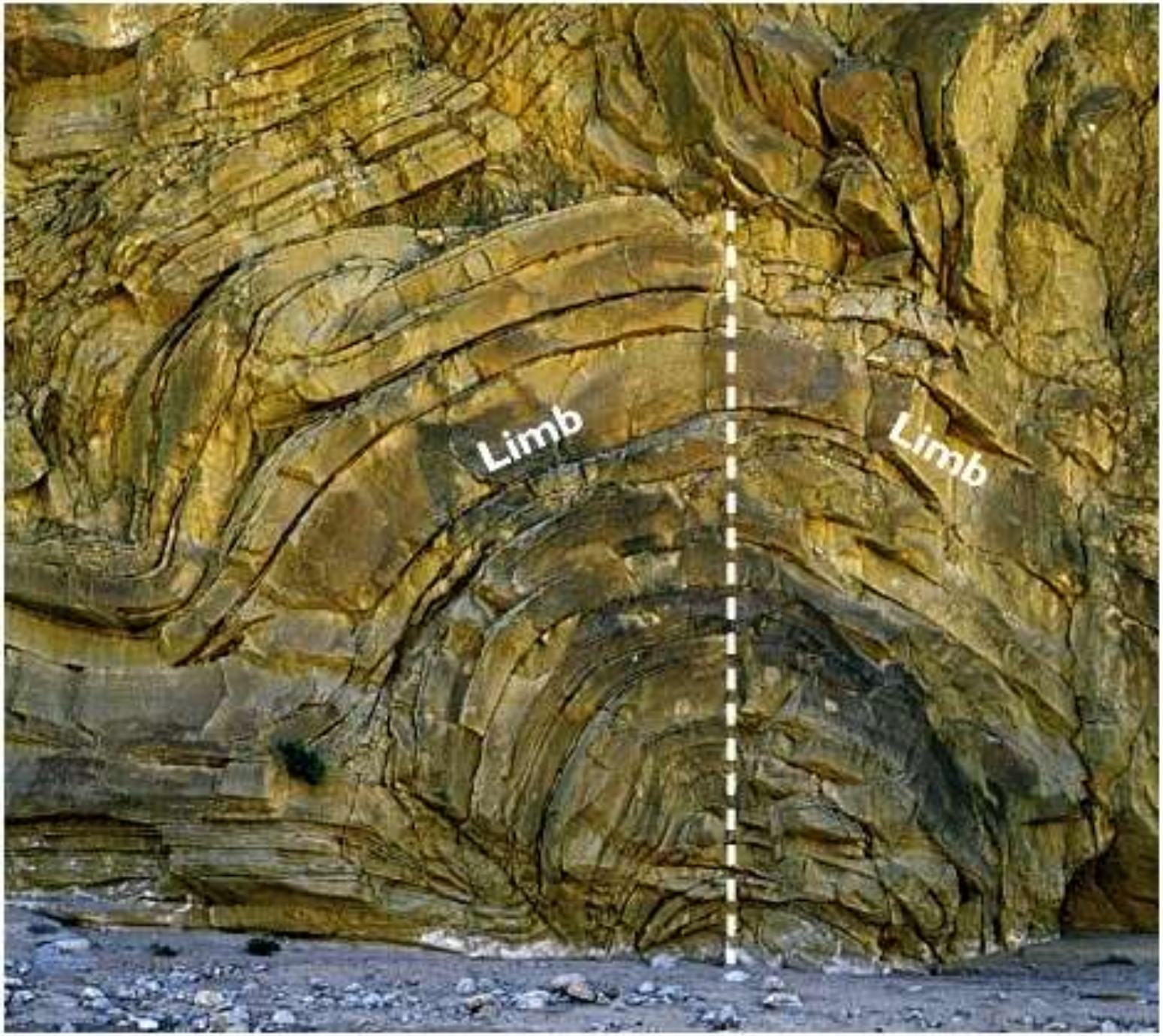


Axial plane is vertical

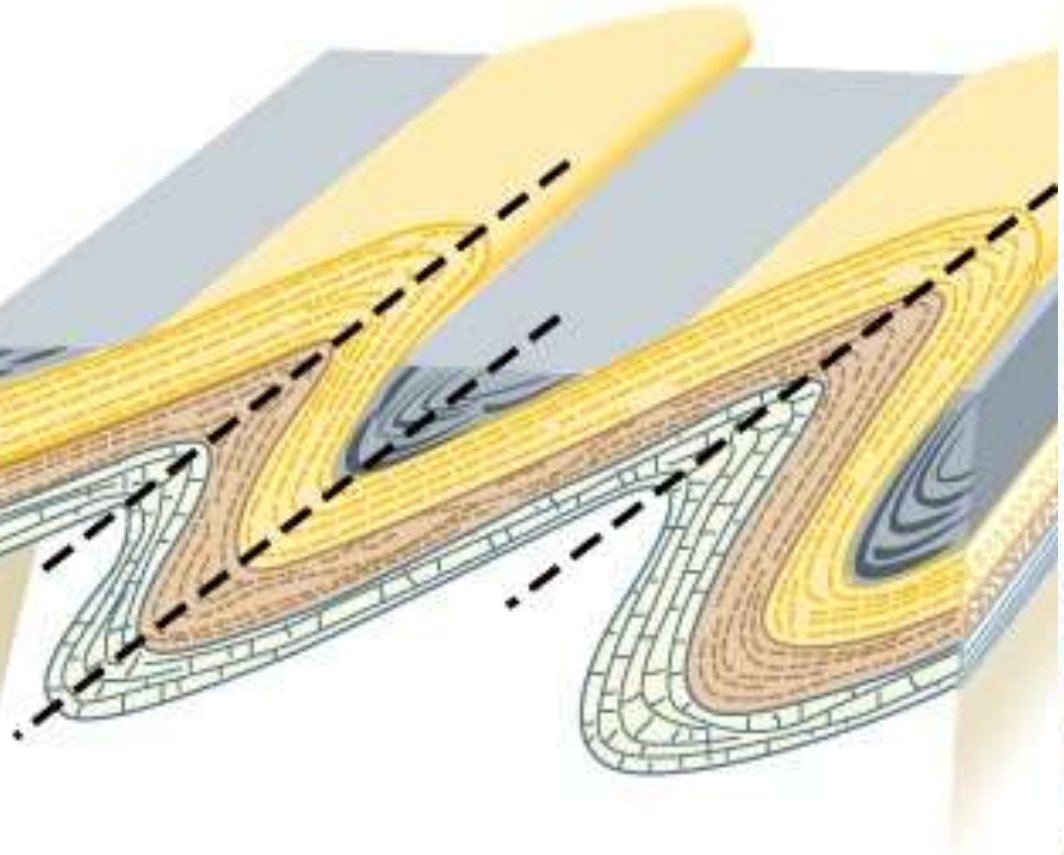


- Appalachian Mountains - a fold belt

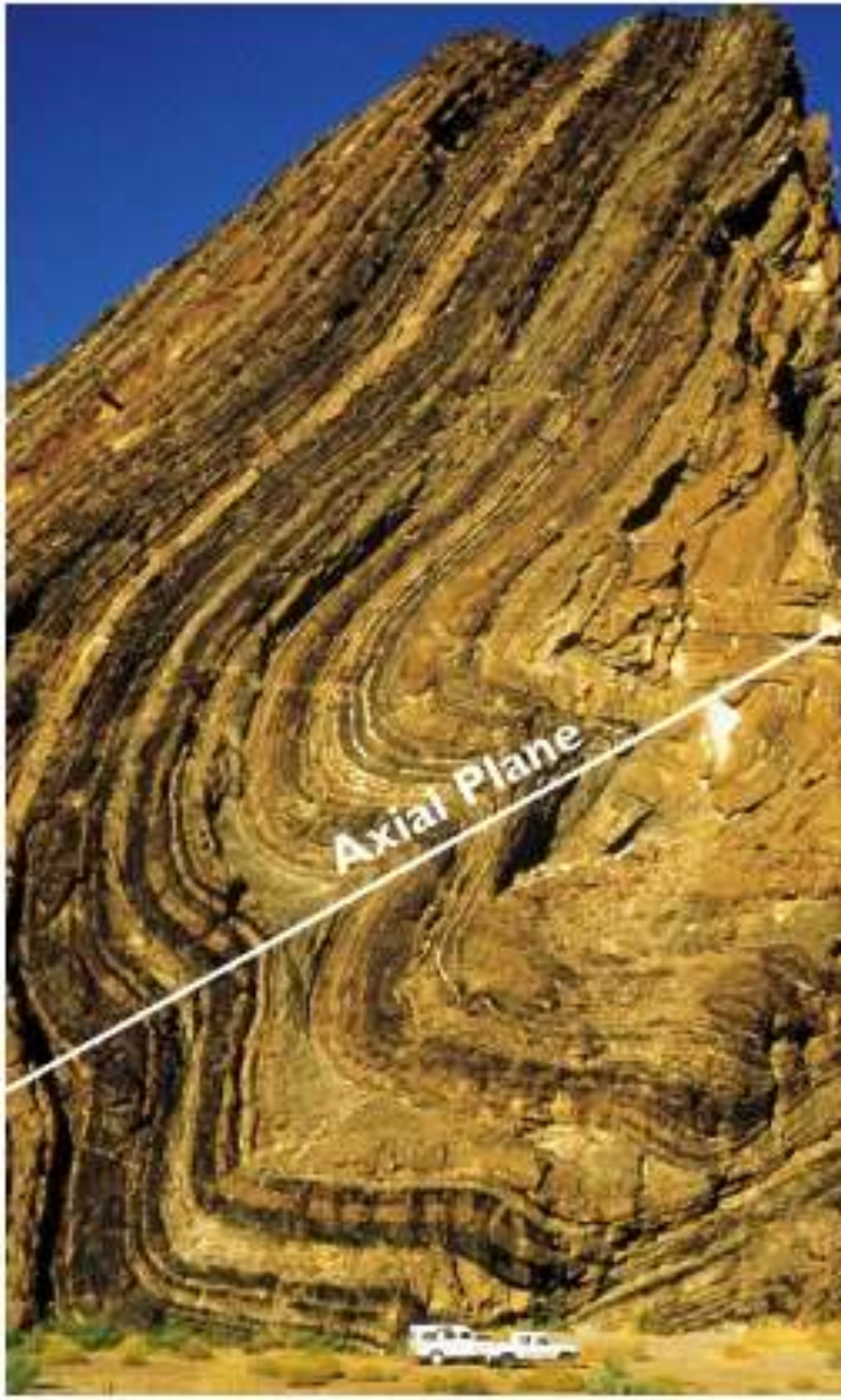



Limb
Limb

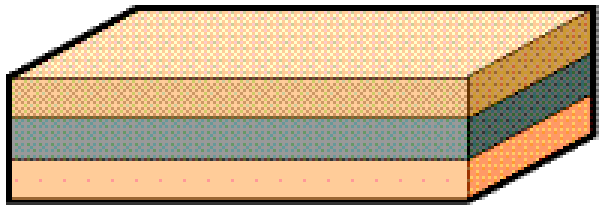
(c) Overturned folds



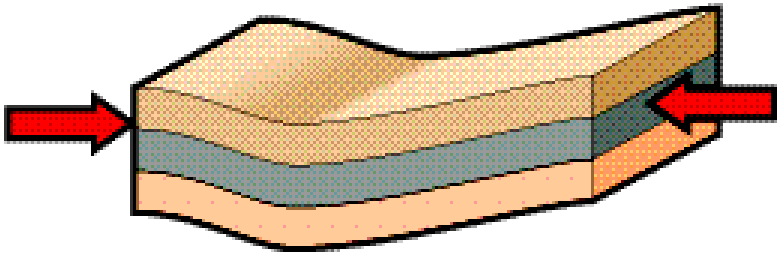
Both limbs dip in same direction but one limb has been tilted beyond vertical



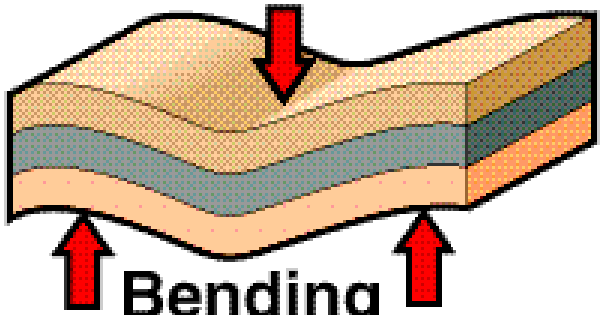
Types of Folds and Movement



A Strata before folding

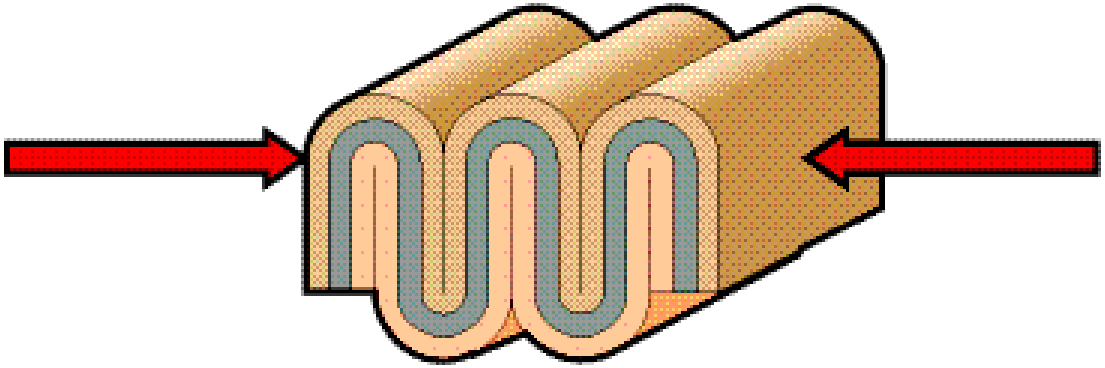


Buckling



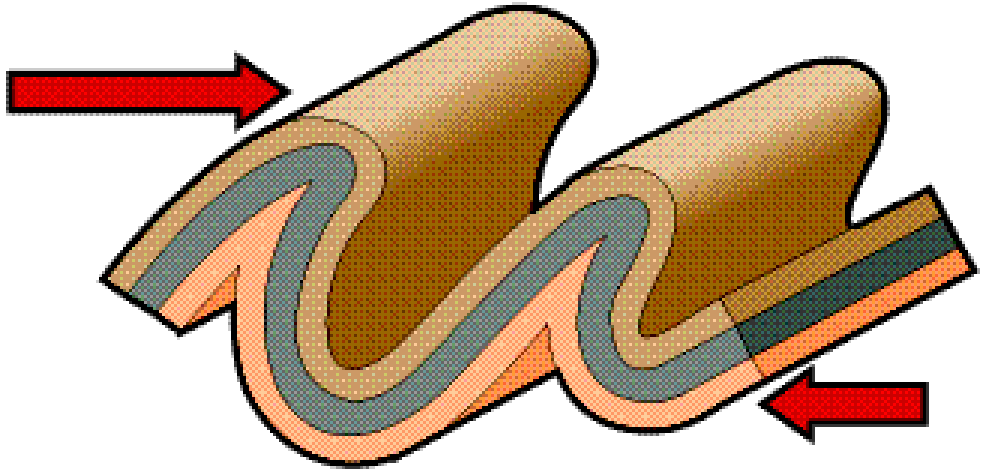
Bending

B Open folds–the two diagrams show alternate ways that stresses may have been distributed to have caused the folding.

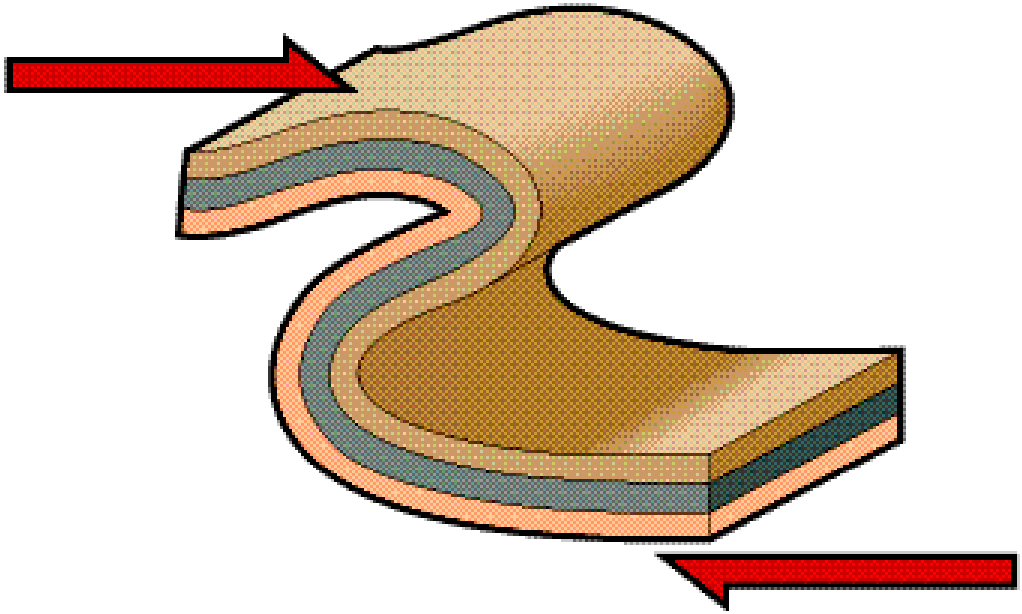


C Isoclinal ("hairpin") folds

Types of Folds and Movements

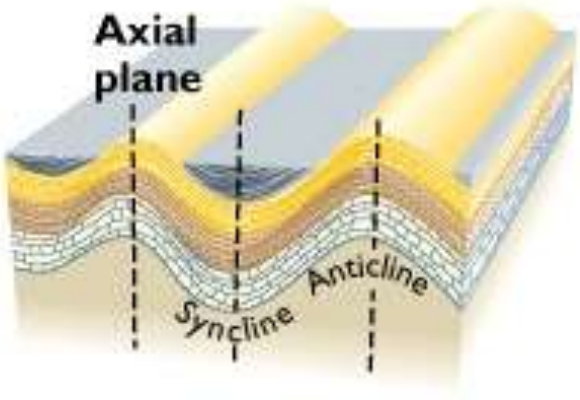


D Overturned folds



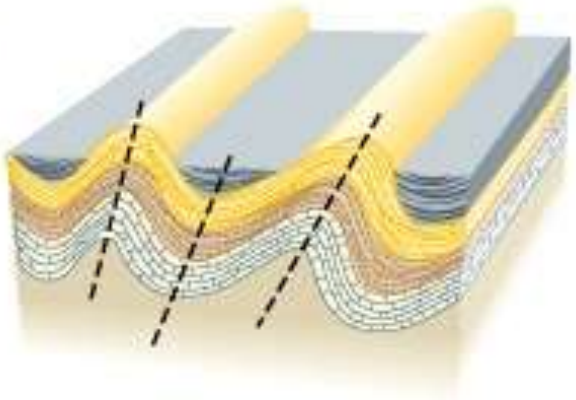
E Recumbent folds

(a) Symmetrical folds



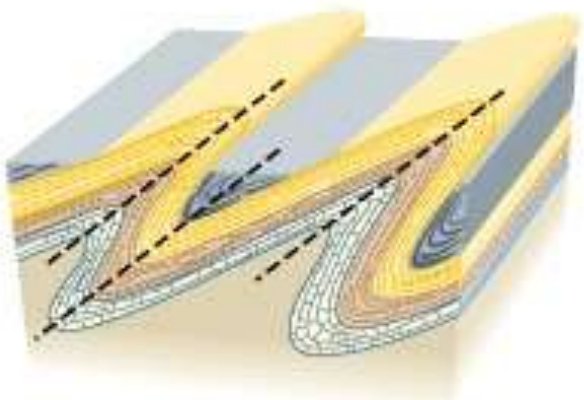
Axial plane is vertical

(b) Asymmetrical folds



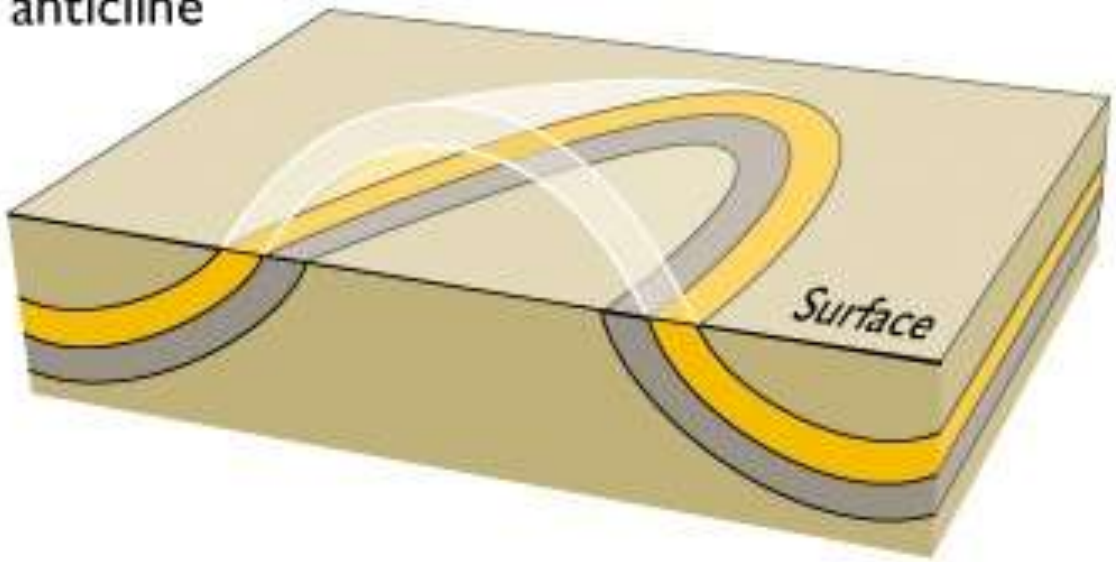
Beds in one limb dip more steeply than those in the others

(c) Overturned folds

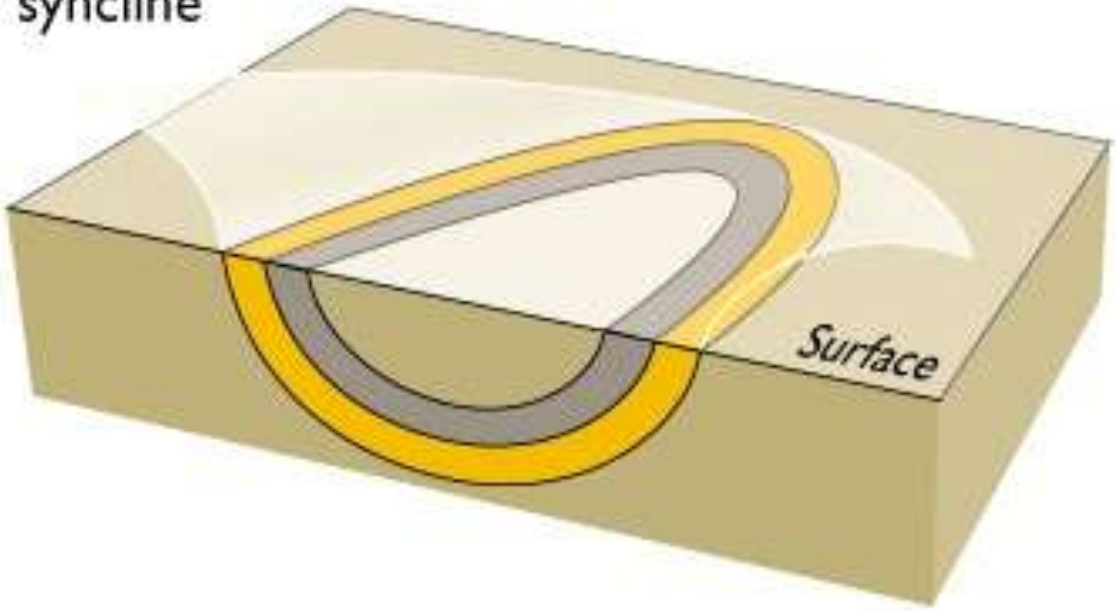


Both limbs dip in same direction but one limb has been tilted beyond vertical

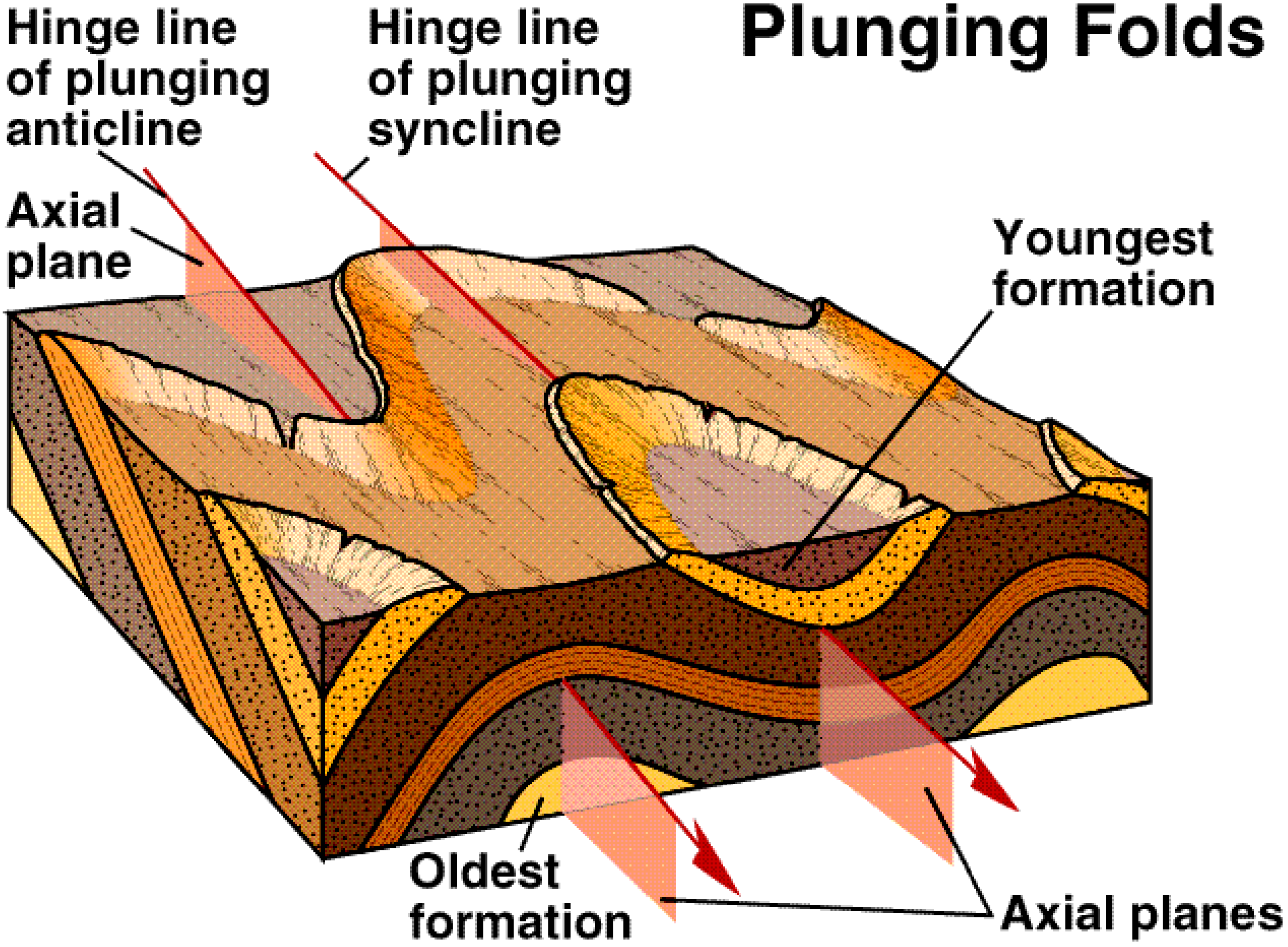
Plunging anticline



Plunging syncline

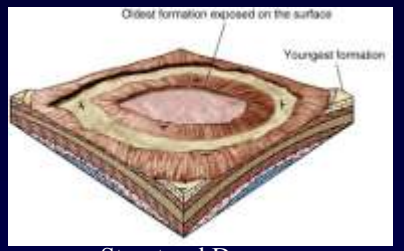


Plunging Folds

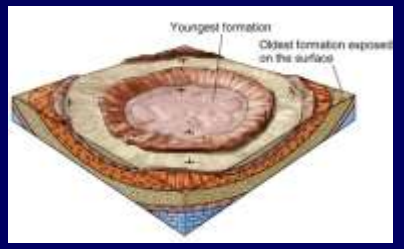


Structural Domes and Basins

- ***Domes*** are structures in which the beds dip away from a central point
  - Sometimes called doubly plunging anticlines
- ***Basins*** are structures in which the beds dip toward a central point
  - Sometimes called doubly plunging synclines

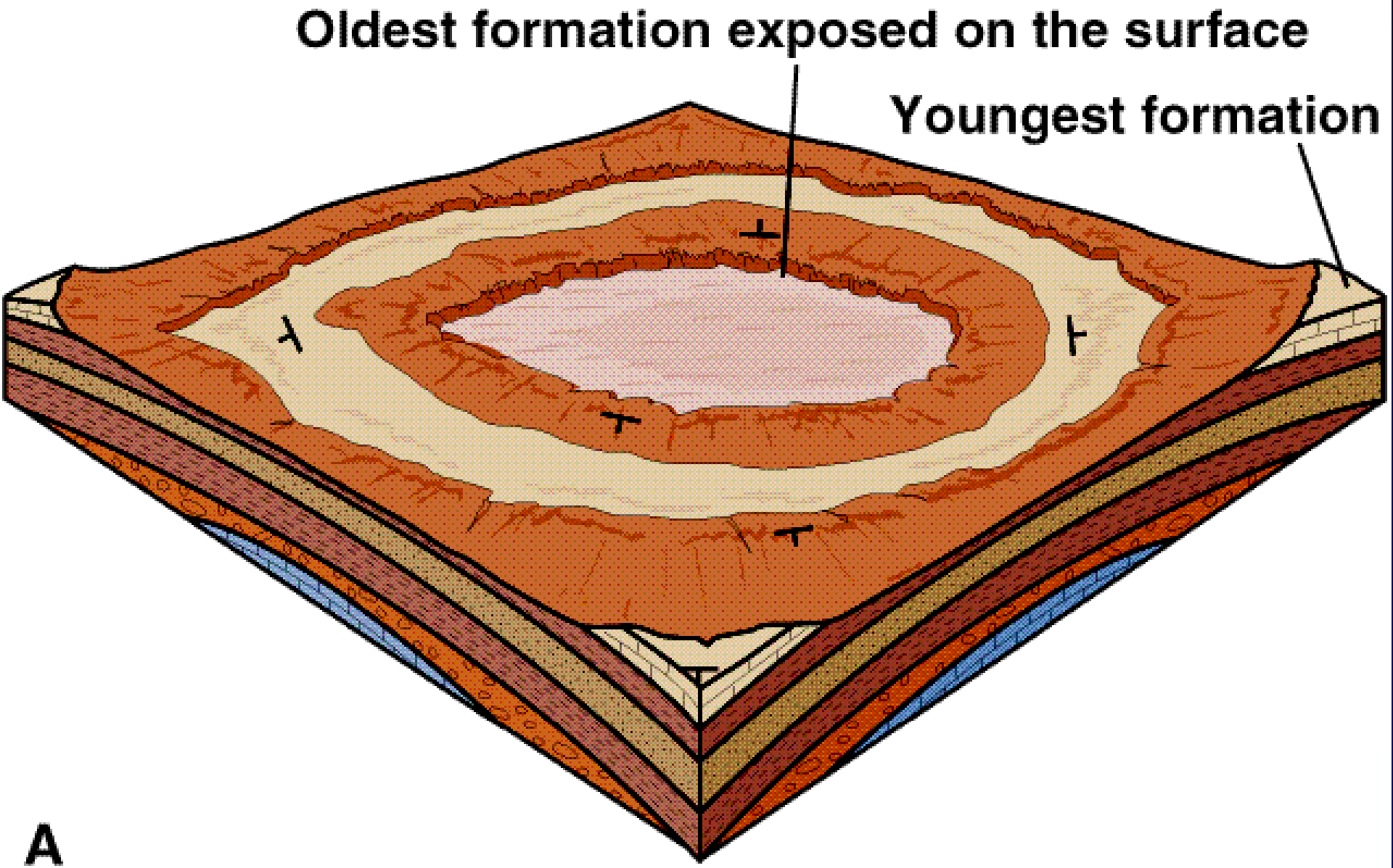


Structural Dome



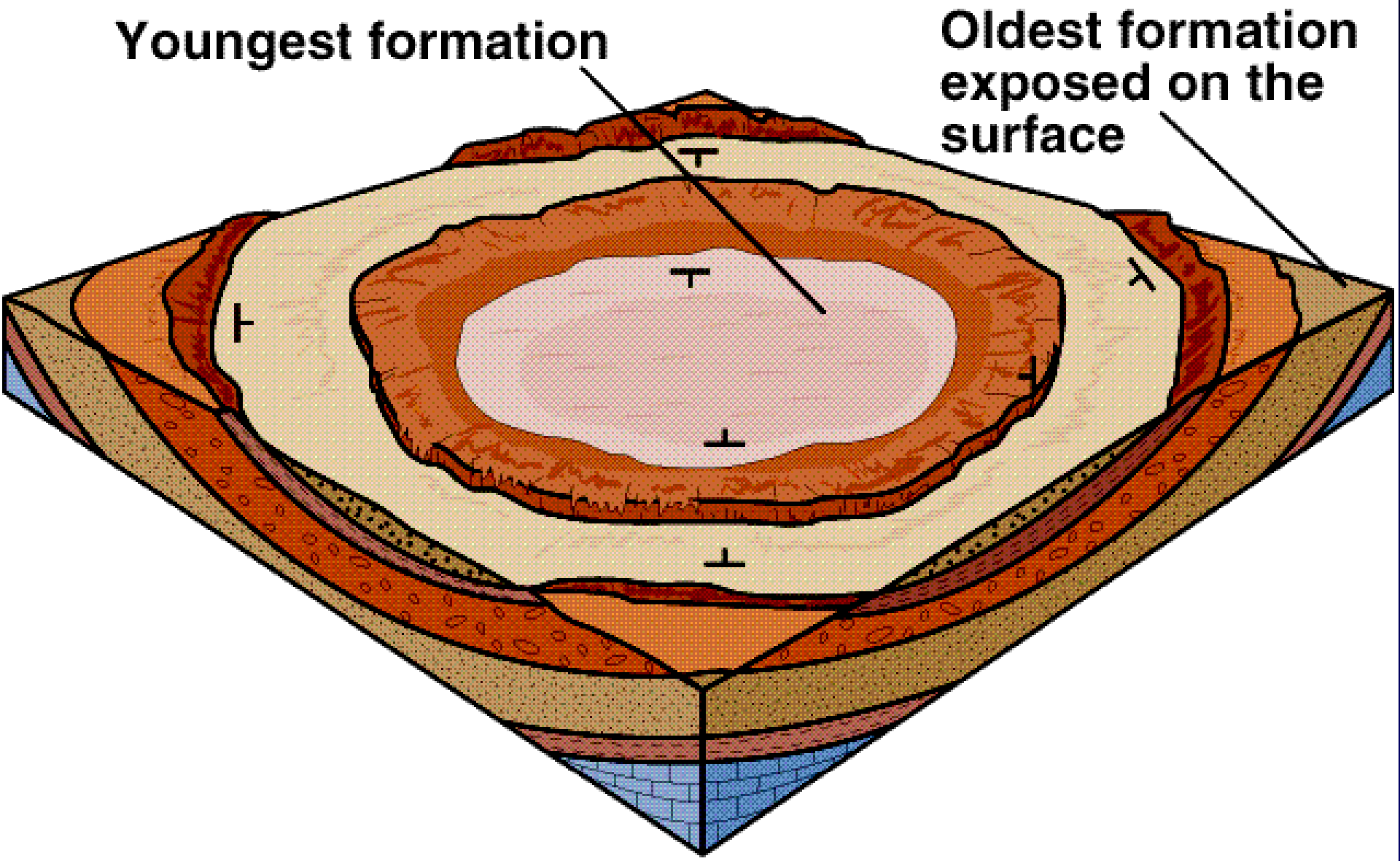
Structural Basin

Structural Dome



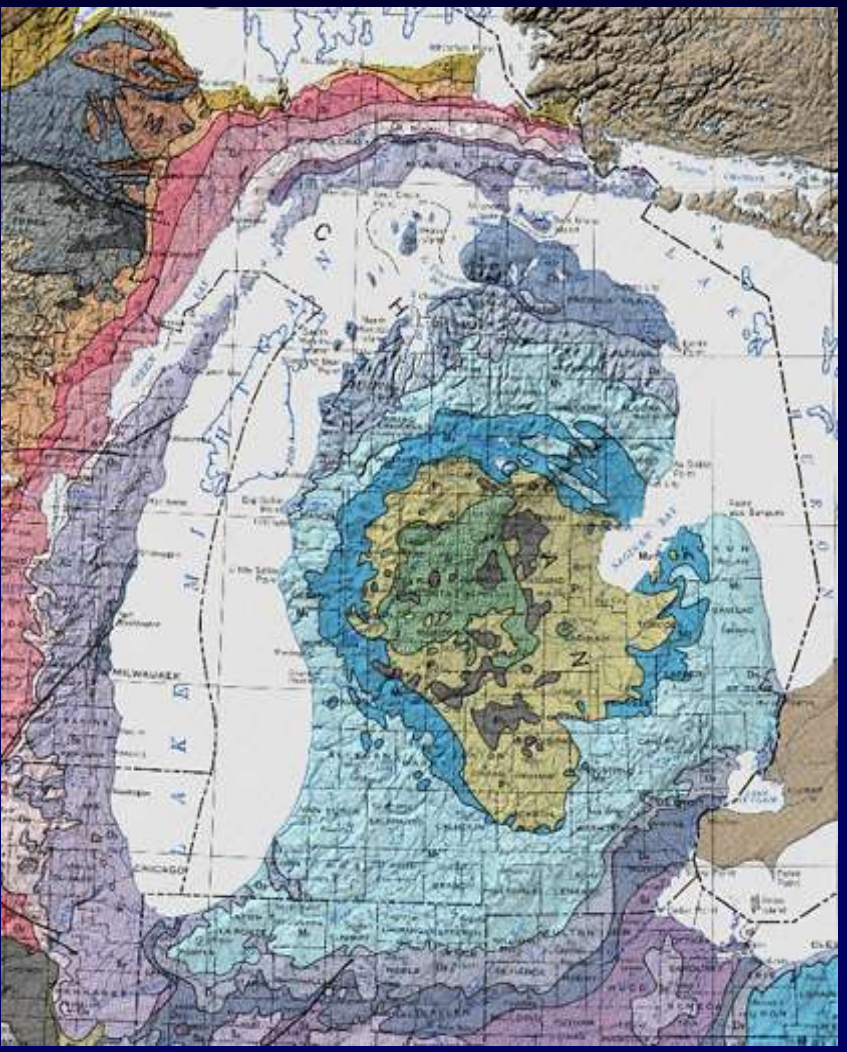
A

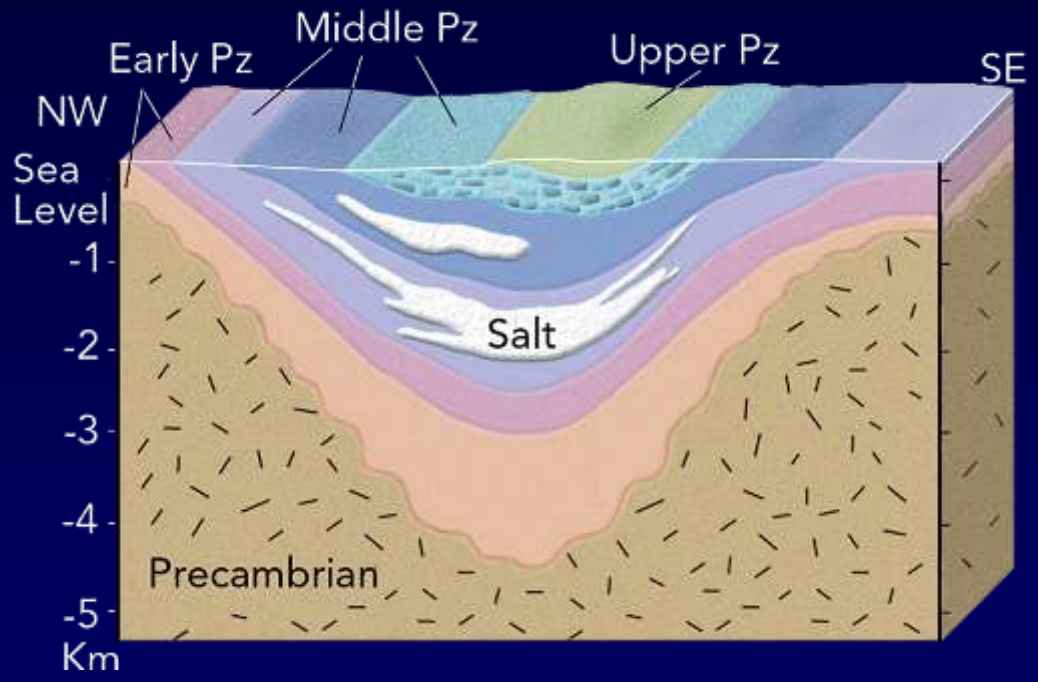
Structural Basin

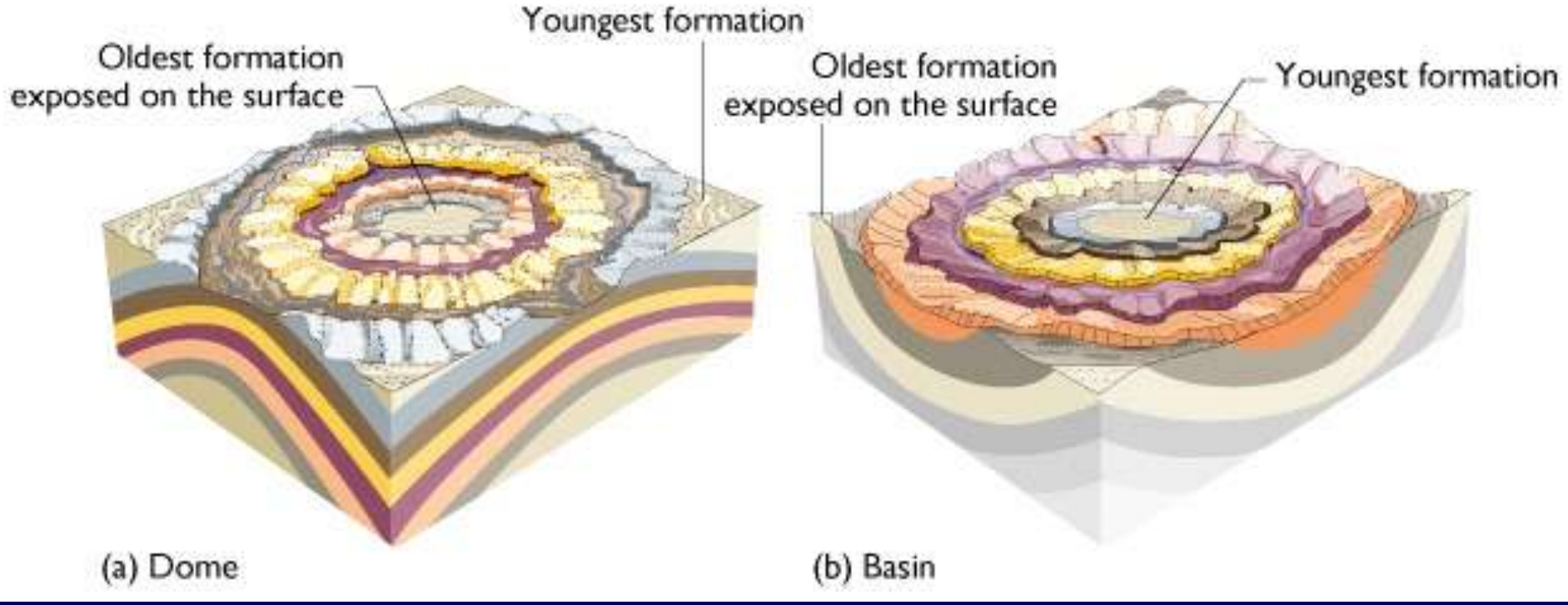


B

The Michigan Basin

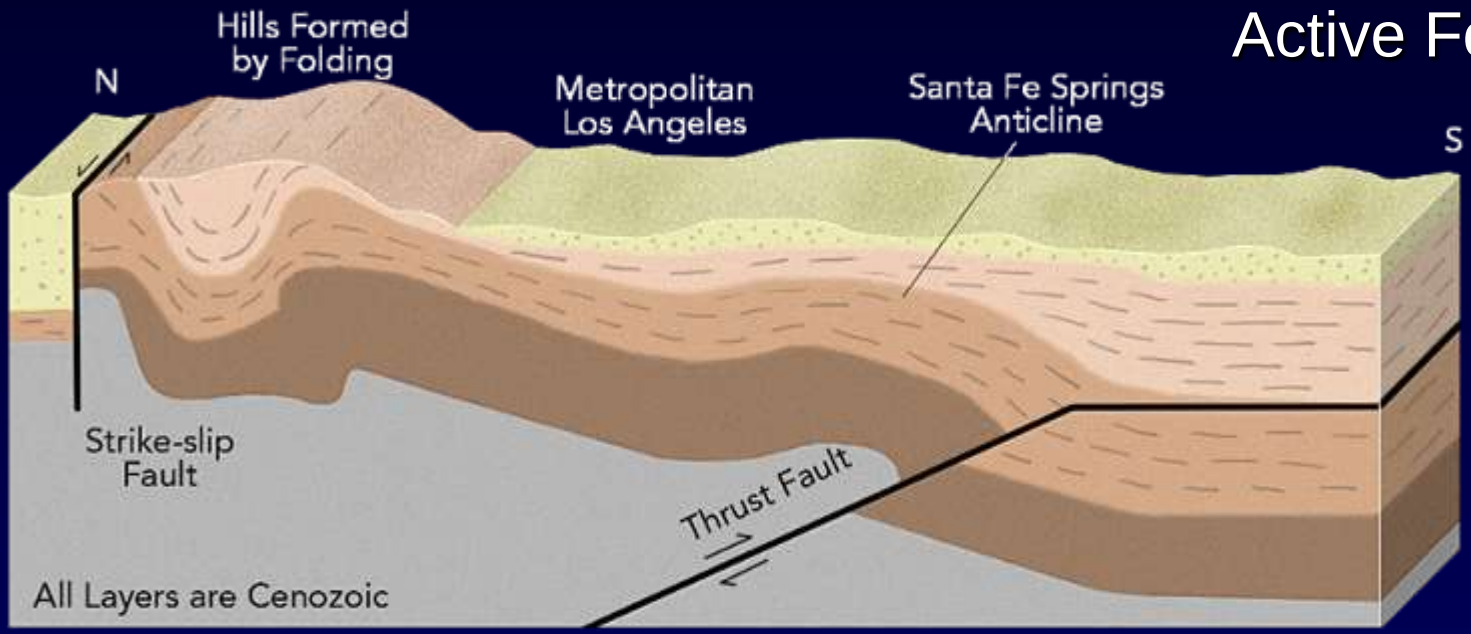





Youngest formation
Oldest formation
exposed on the surface
Oldest formation
exposed on the surface
Youngest formation
(a) Dome
(b) Basin

How Folding Can Form Mountains

Active Folding



11.03.c

Erosion of previously folded rock layers

Fractures in rock

- Joints
  - Columnar jointing
  - Sheet jointing
  - Joint set
- Faults
  - Dip-slip faults- normal and reverse

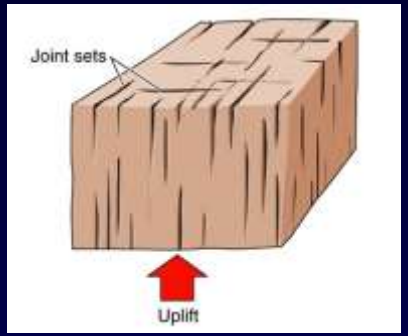
    Footwall vs. hanging wall
  - *Normal fault*

    Graben; Rift

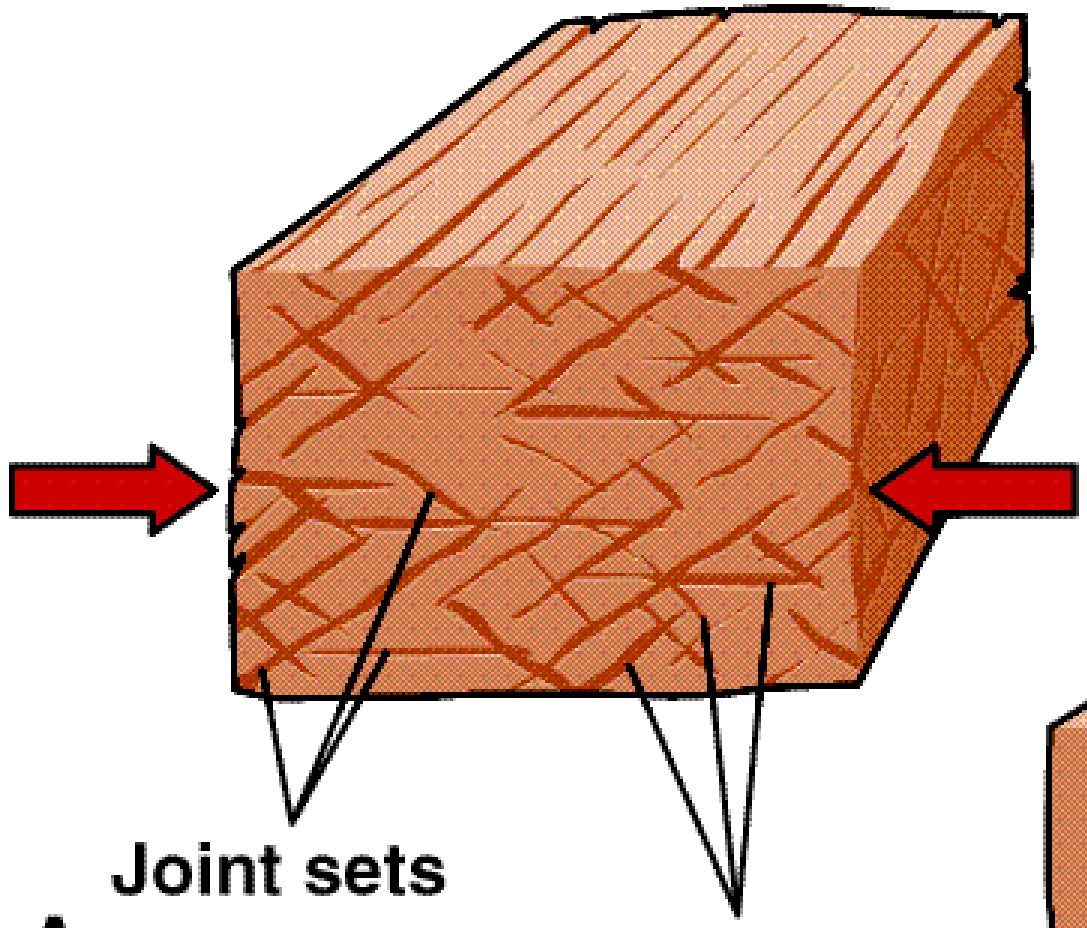
    Horst ; fault-block mountain range

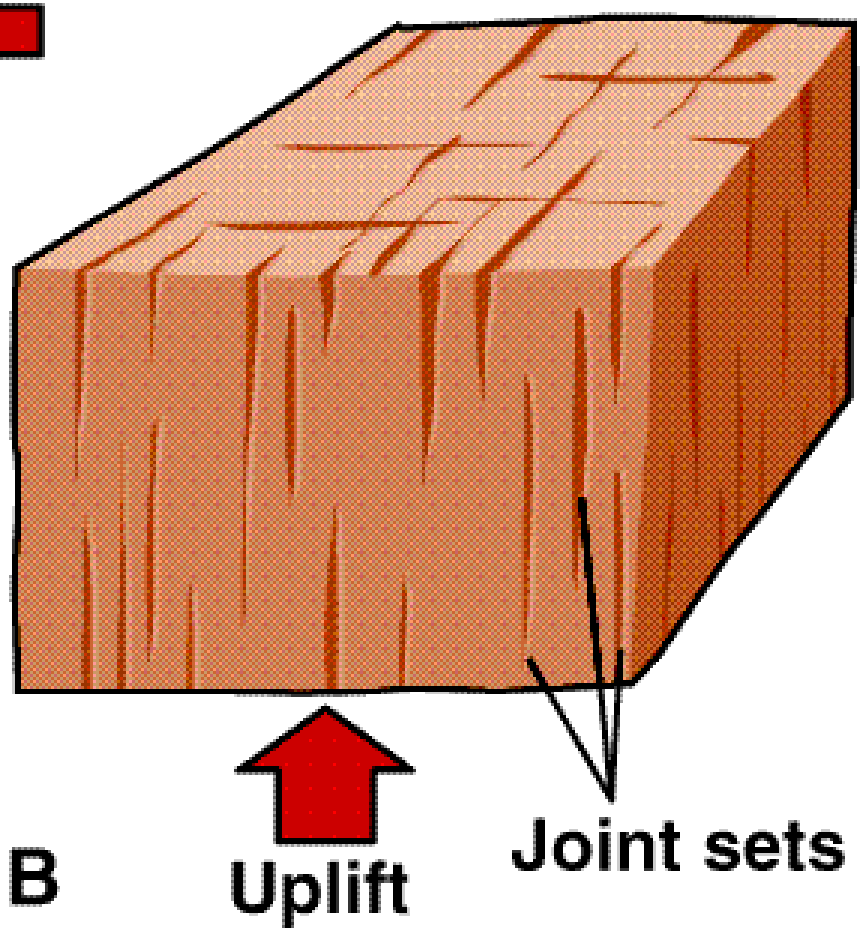
Fractures in Rock

- ***Joints*** are fractures or cracks in bedrock along which essentially no movement has occurred
  - Multiple parallel joints are called *joint sets*
- ***Faults*** are fractures in bedrock along which movement has occurred
  - Considered “active” if movement has occurred along them within the last 11,000 years (since the last ice age)
  - Categorized by type of movement as ***dip-slip***, ***strike-slip***, **or** ***oblique-slip***



Joint Sets



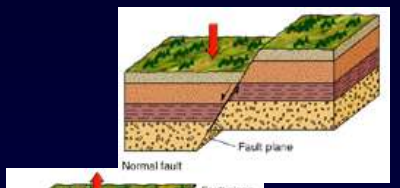


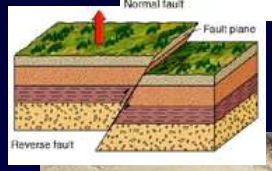
Breaks in Rocks: Joints and Faults

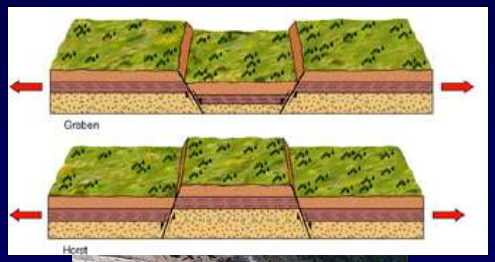
- Joints: breaks with no movement (v. common)
- Faults: breaks with non-trivial movement
  - Classified by orientation and direction of movement (tells about stress regime)
  - *Dip-slip* (along dip): **reverse** if top block moves up (**thrust** if low-angle); **normal** if top block moves down
  - *Strike-slip* (horizontal movement): **strike-slip fault**
  - *Oblique-slip* (in some other direction)
- Names of blocks--from mining terminology (above / below)
  - **Hanging wall (top block)**
  - **Footwall (bottom block)**

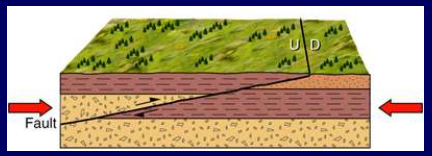
Types of Faults

- ***Dip-slip faults*** have movement parallel to the dip of the fault plane
  - Most common types are normal and reverse
    - In ***normal faults,*** the *hanging-wall block* has moved down relative to the *footwall block*
    - In ***reverse faults***, the hanging-wall block has moved up relative to the footwall block
  - Fault blocks, bounded by normal faults, that drop down or are uplifted are known as ***grabens* and *horsts*,** respectively
    - **Grabens** associated with divergent plate boundaries are called ***rifts***
  - ***Thrust faults*** are reverse faults with dip angles *less than 30°* from horizontal

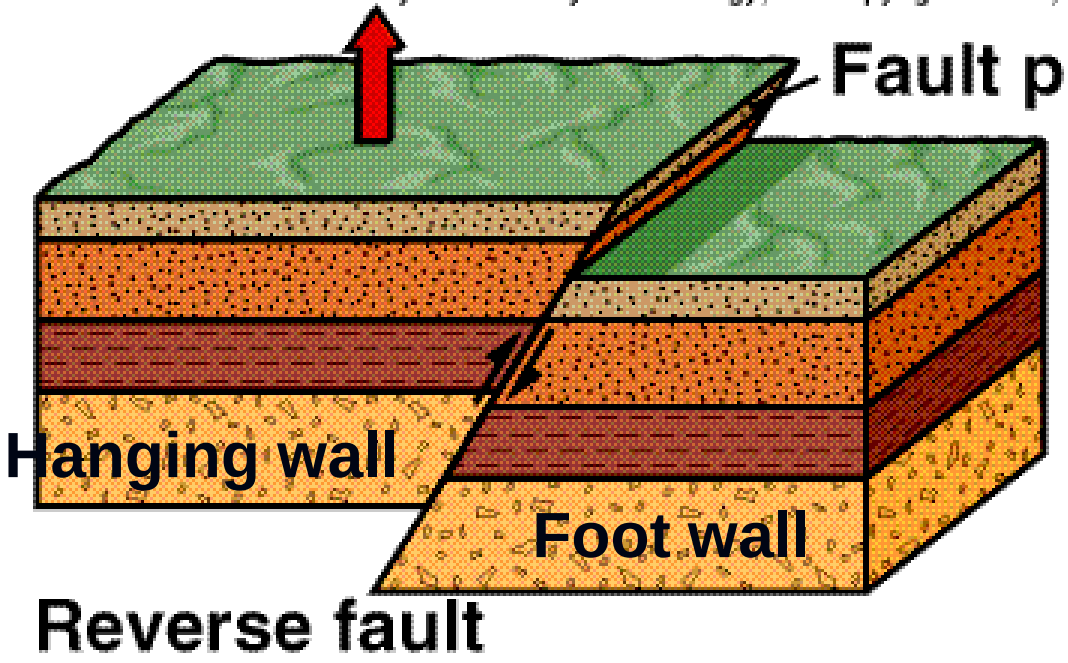




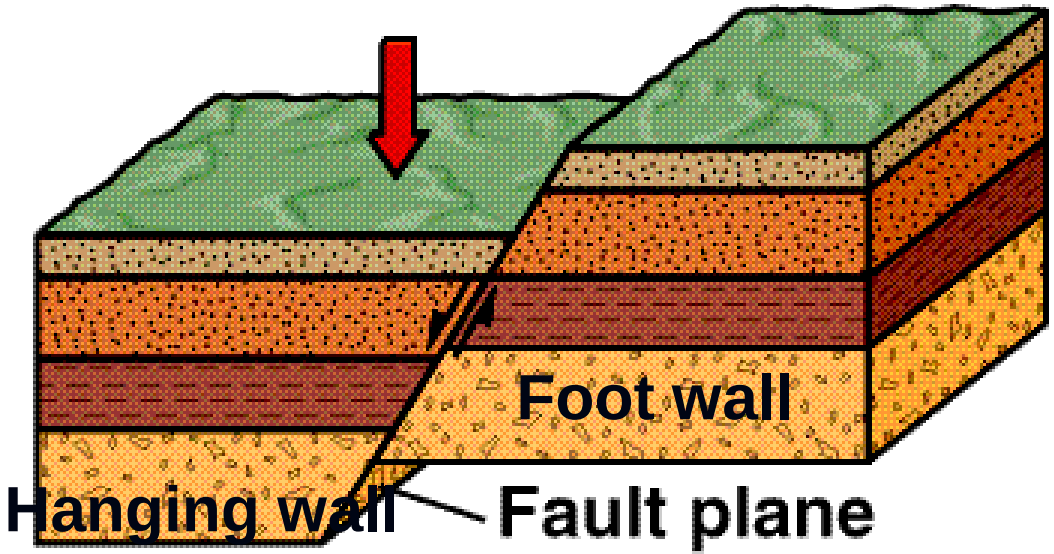




Dip-Slip Fault



Reverse fault



Normal fault

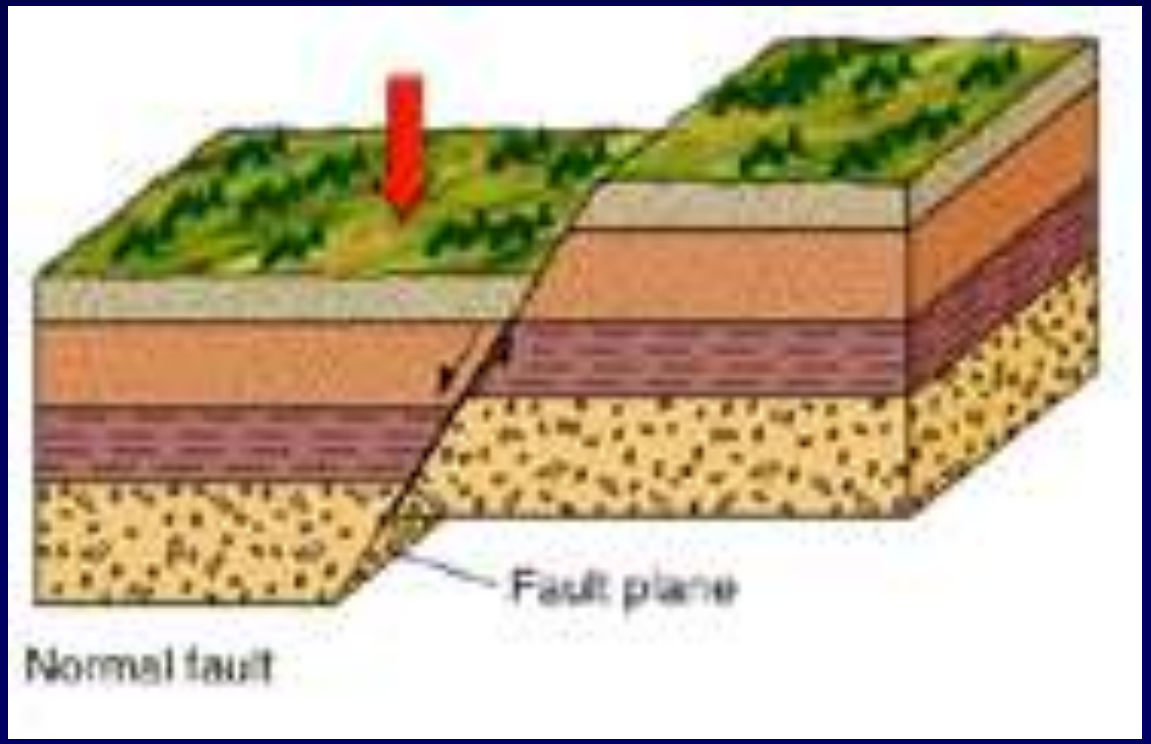
Dip-slip faults

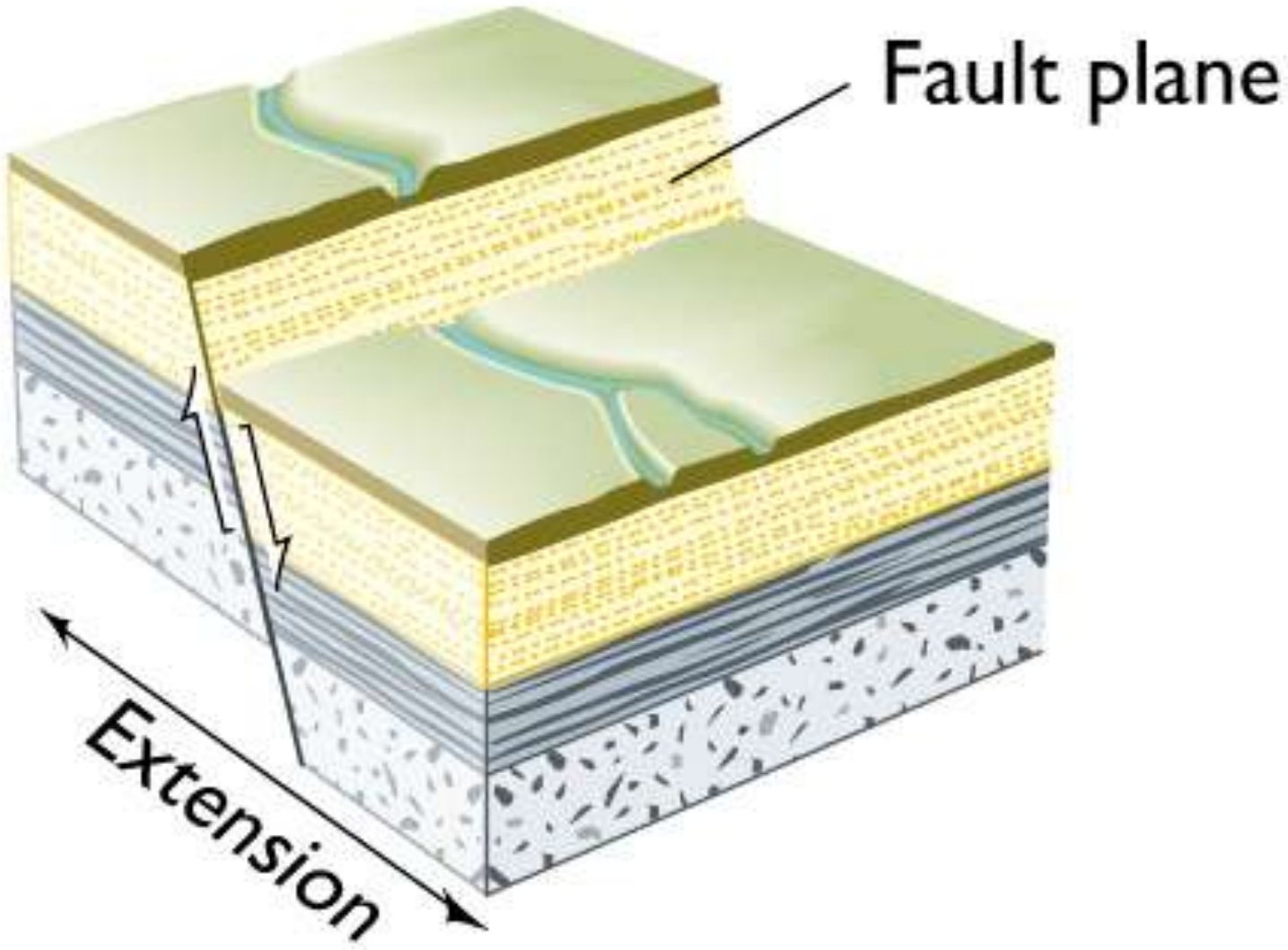
A

Types of Faults

- ***Dip-slip faults*** have movement parallel to the dip of the fault plane
  - Most common types are normal and reverse

    In ***normal faults*****, the *hanging-wall block* has moved down relative to the *footwall block***

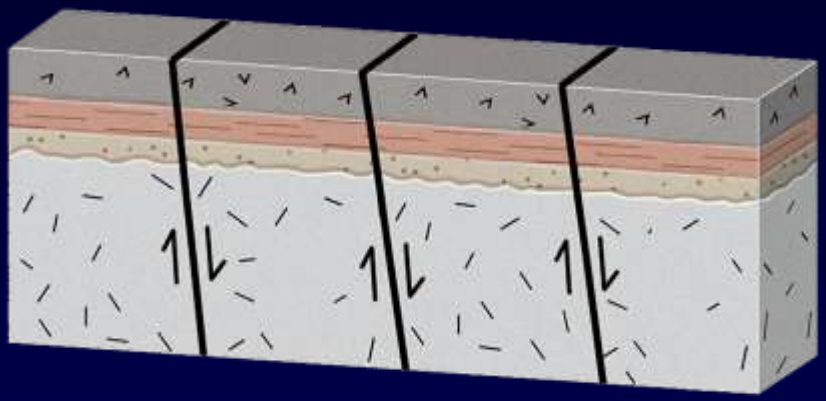




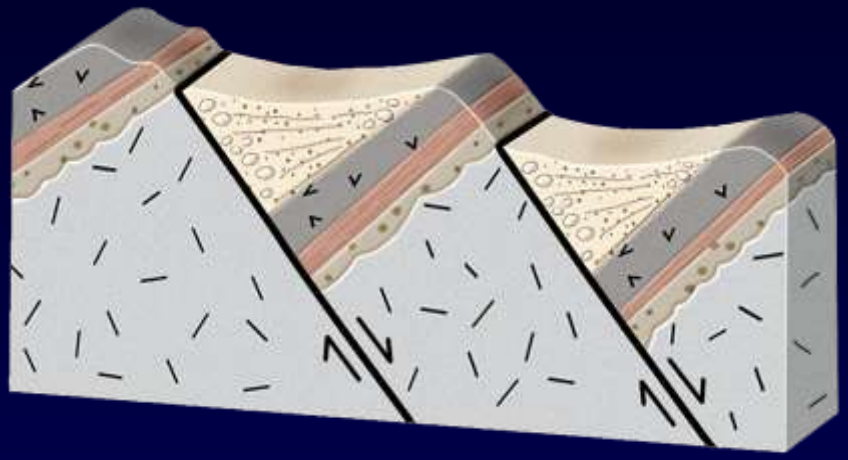
(a) DIP-SLIP FAULT
(normal)

Dip Slip (Normal) Fault

Extension on Rotating Fault Blocks



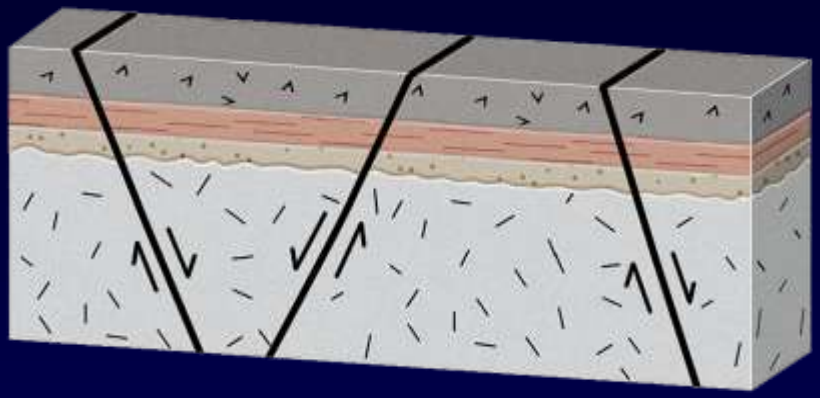
Normal faults all dip in the same direction



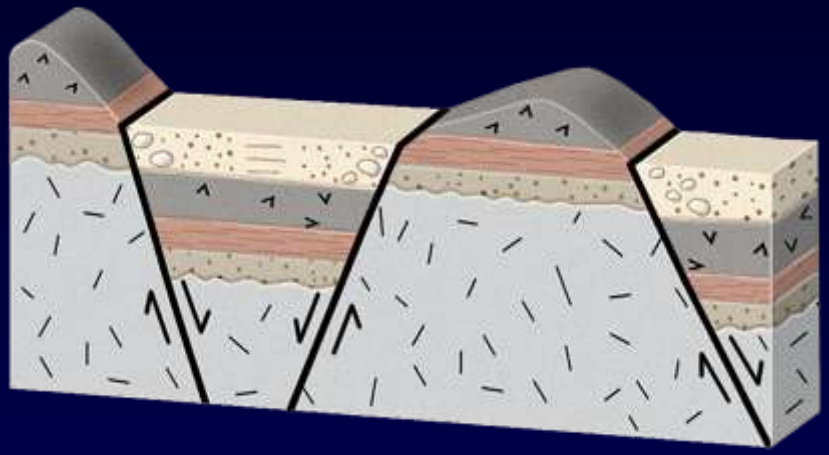
Corner that is rotated up becomes a mountain

11.06.c

Extension on Non-Rotating Fault Blocks

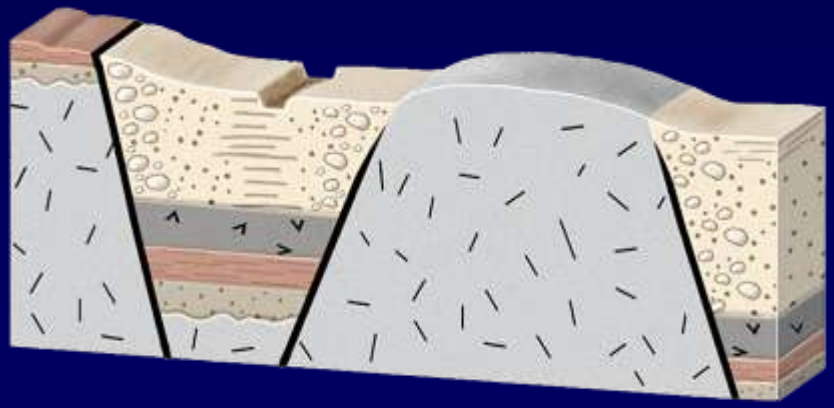


Normal faults dip in opposite directions



Movement along faults forms basins and mountains

11.06.c

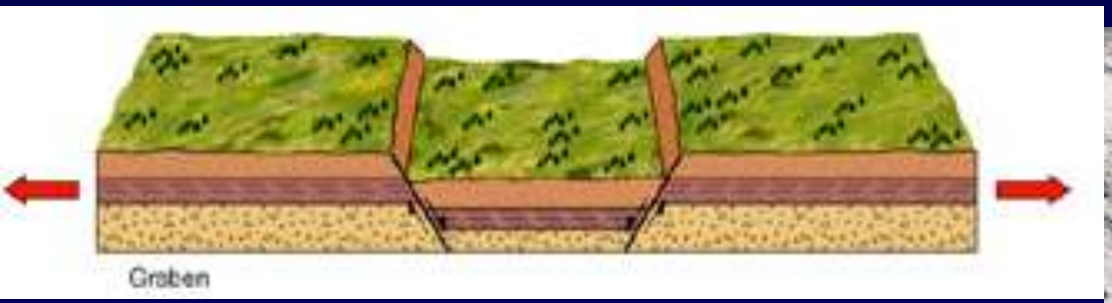


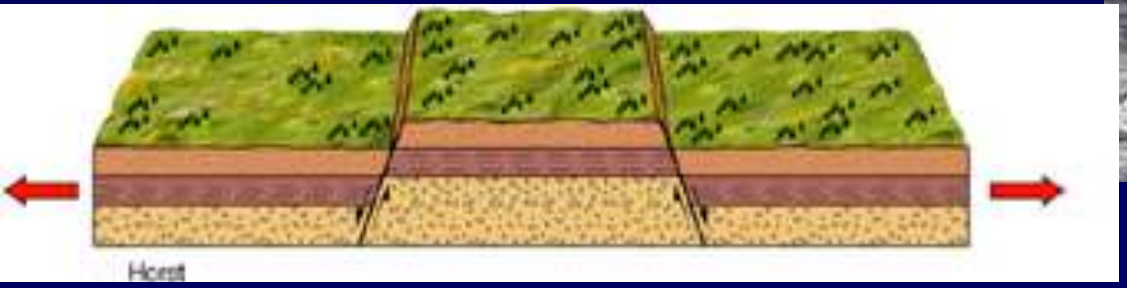
Over time, basins fill and mountains erode

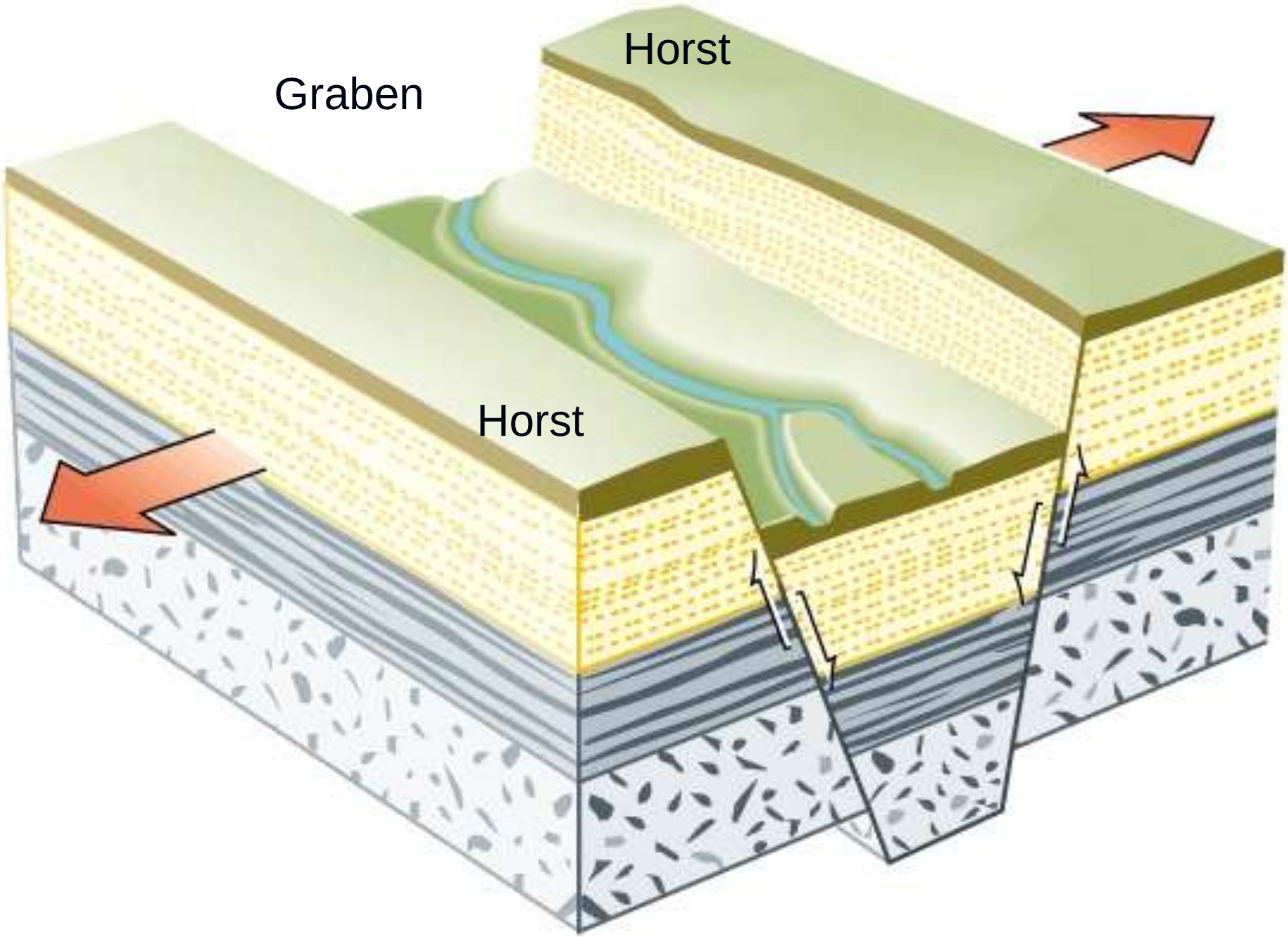
Types of Faults

- ***Dip-slip faults*** have movement parallel to the dip of the fault plane
  - Fault blocks, bounded by normal faults, that drop down or are uplifted are known as *grabens* and *horsts*, respectively

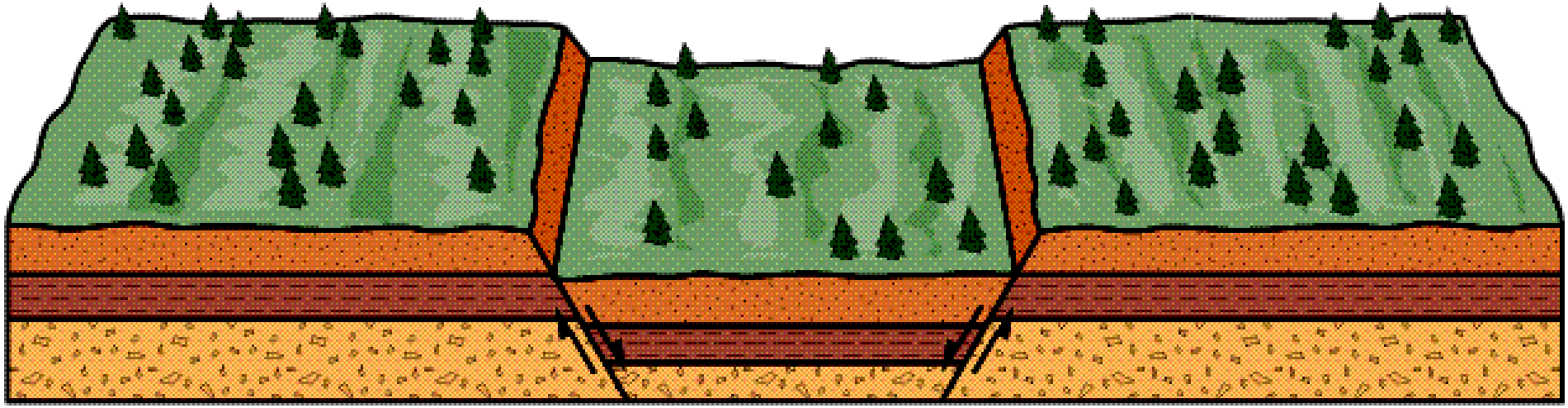
    Grabens associated with divergent plate boundaries are called *rifts*



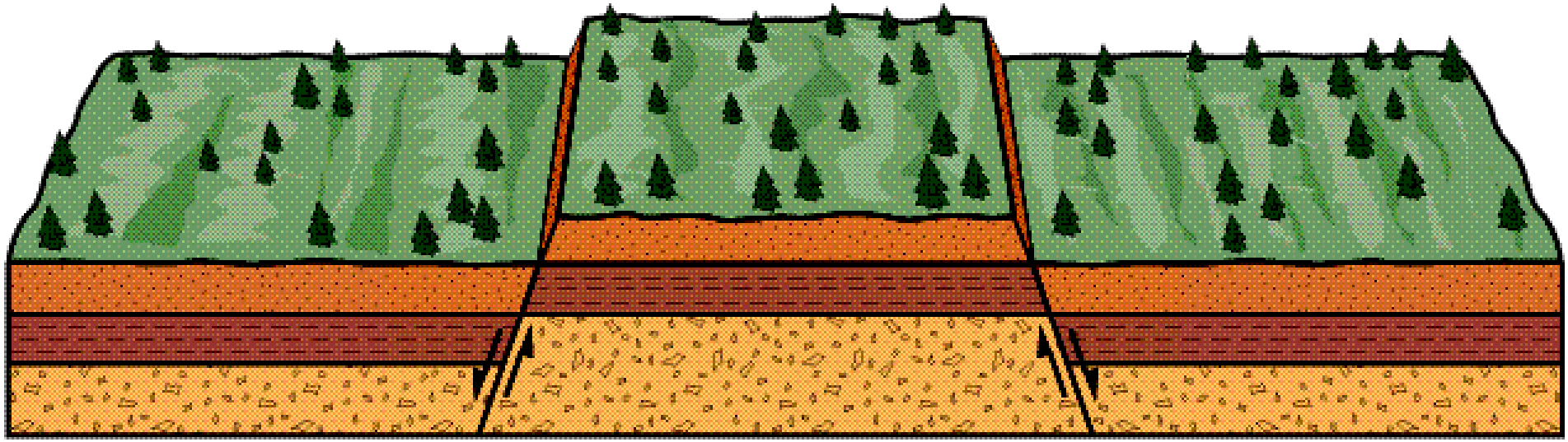



Horst
Graben
Horst

Graben, Horst Faults



Graben

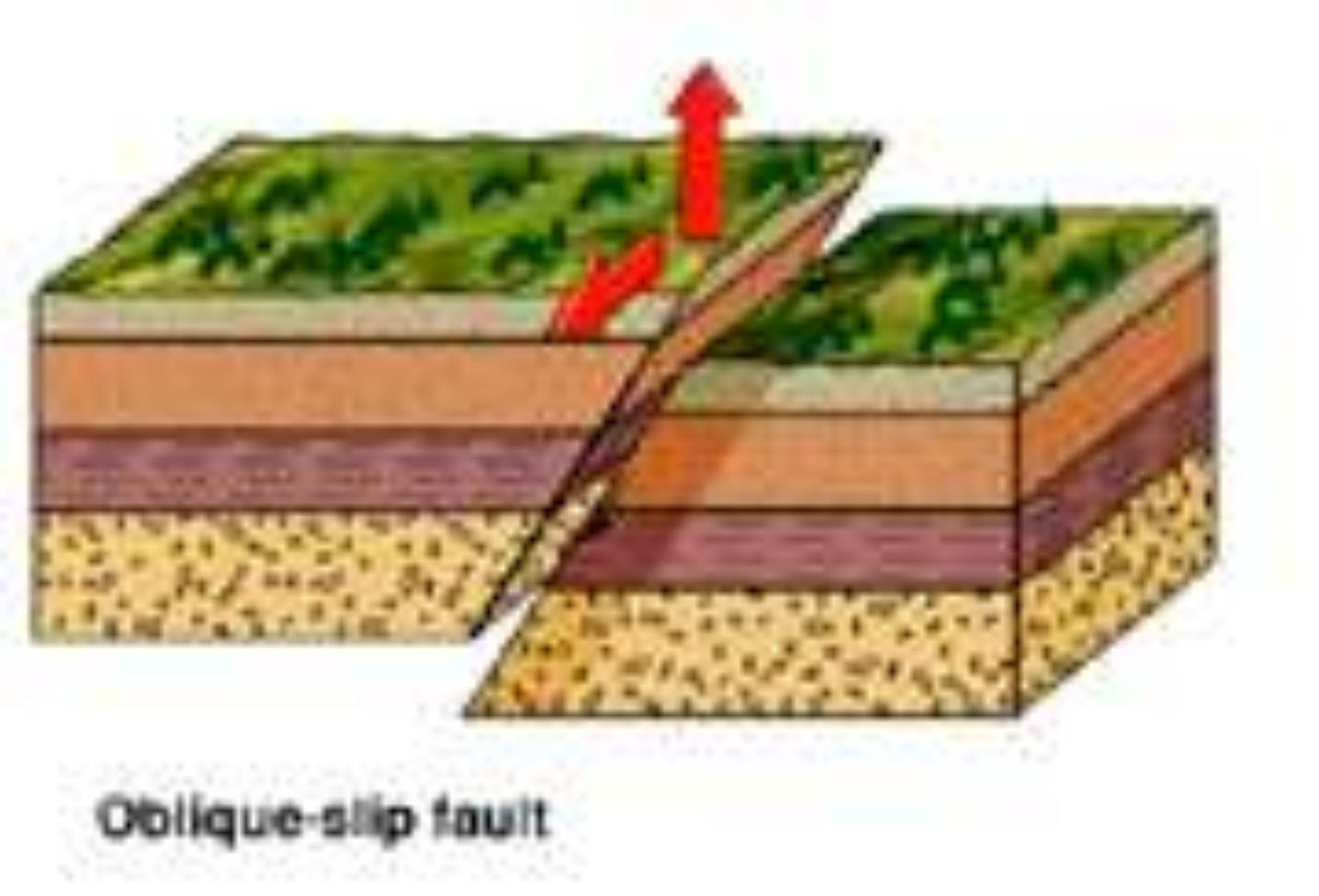


Horst

Horst Block Offsets Volcanic Ash

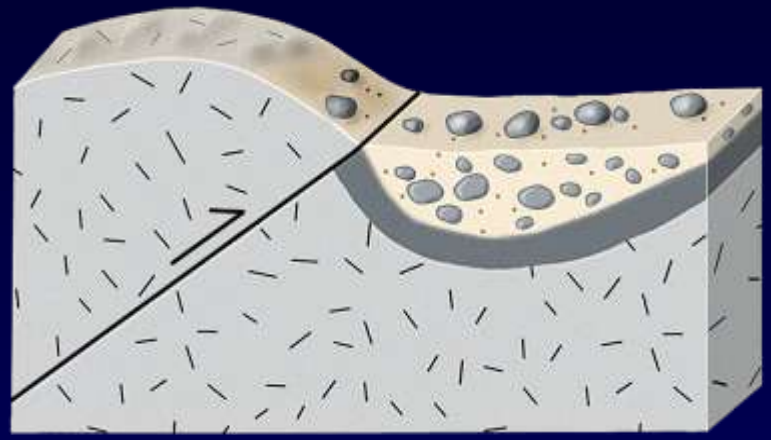
Oblique Slip Faults

- ***Oblique-slip faults*** have movement that with components parallel to both the strike and dip of the fault plane



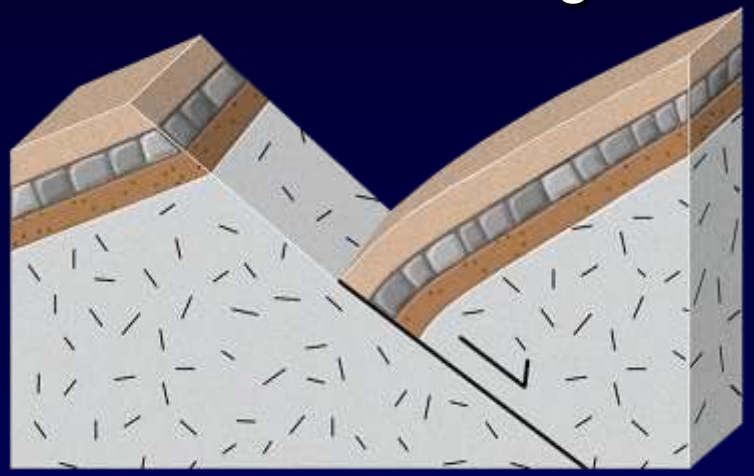
How Faulting Can Form Mountains

Thrust Faulting



11.03.b

Normal Faulting

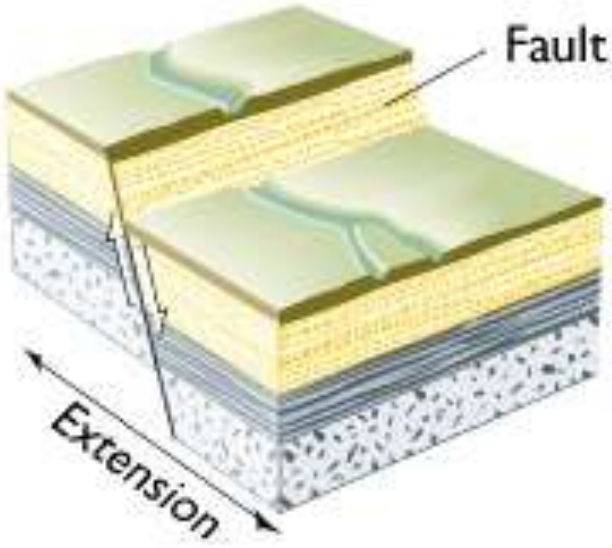


Death Valley

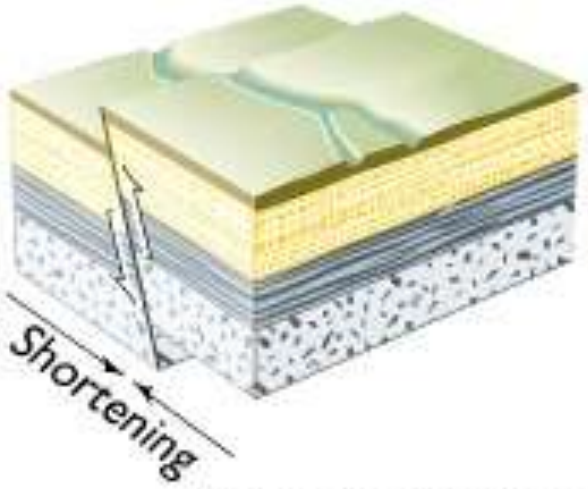
Oblique Slip Faults

- ***Oblique-slip faults*** have movement that with components parallel to both the strike and dip of the fault plane

(d) OBLIQUE-SLIP FAULT



(a) DIP-SLIP FAULT
(normal)



(b) DIP-SLIP FAULT
(reverse)

(c) STRIKE-SLIP FAULT
(left-lateral)

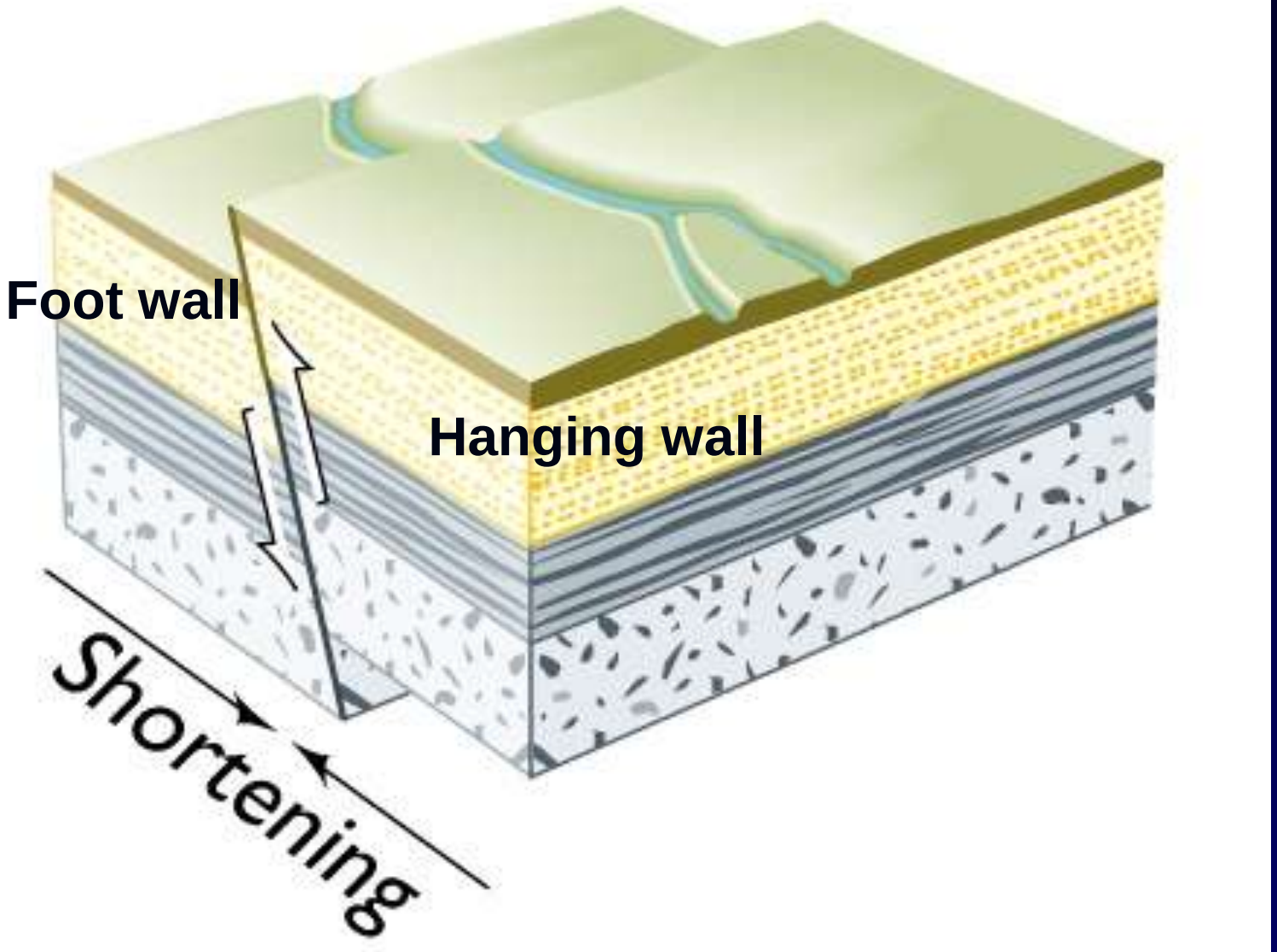
(d) OBLIQUE-SLIP FAULT

Fractures in rock with movement

- Faults
  - Normal fault
  - *Reverse fault*

    Thrust fault = a low-angle reverse fault
  - *Strike-Slip fault*

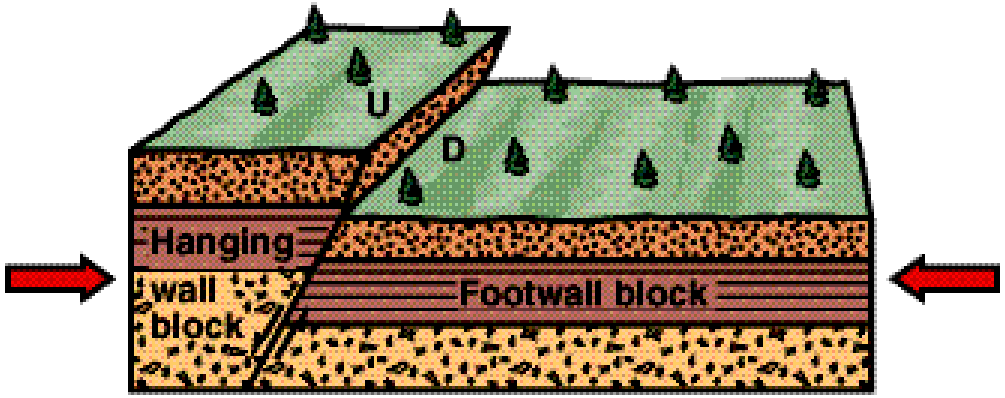
    Left-lateral vs. right-lateral



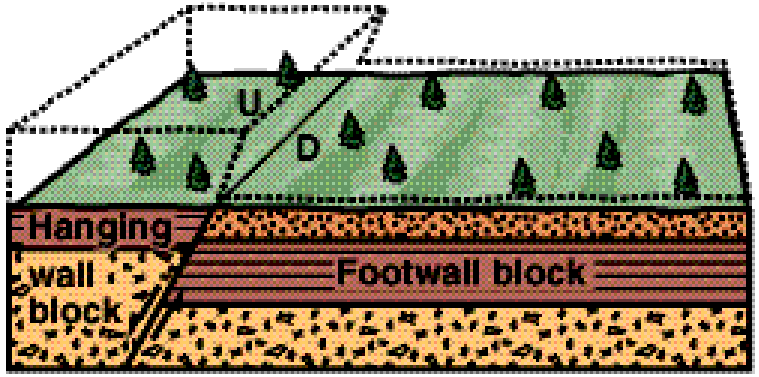
(b) DIP-SLIP FAULT
(reverse)

Reverse Fault in Volcanic Ash Beds

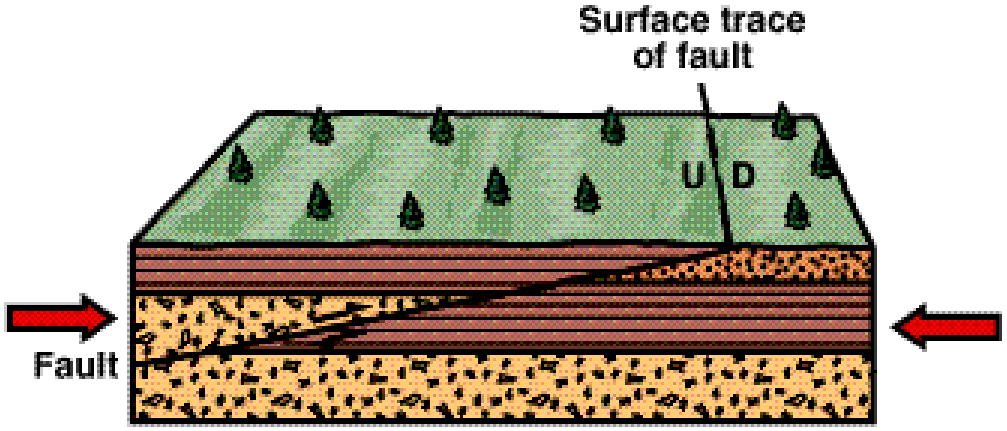
Reverse and Thrust Faults



A



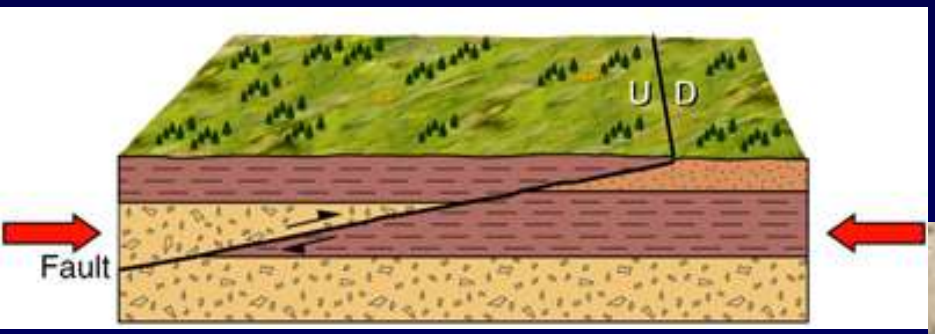
B

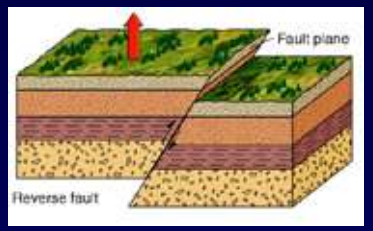


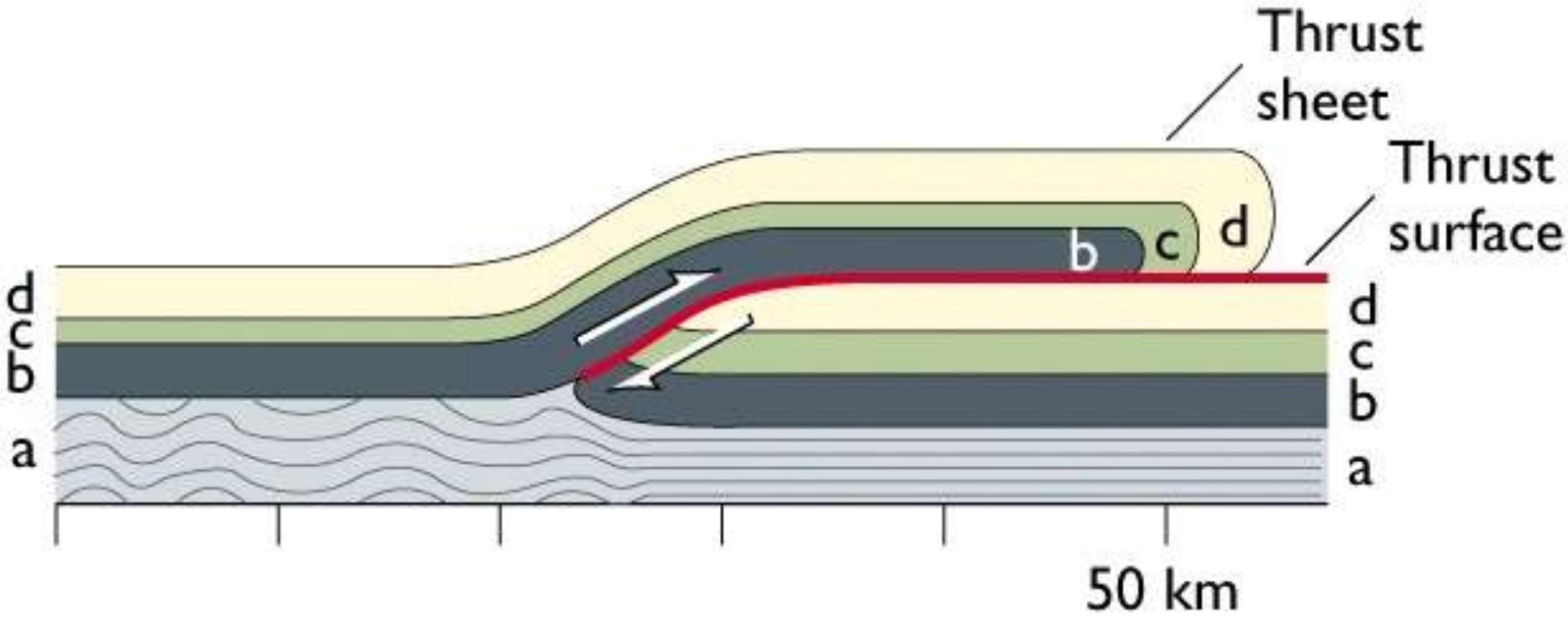
C

Types of Faults

- ***Dip-slip faults*** have movement parallel to the dip of the fault plane
  - In ***reverse faults***, the hanging-wall block has moved up relative to the footwall block
    - ***Thrust faults*** are reverse faults with dip angles *less than 30°* from horizontal



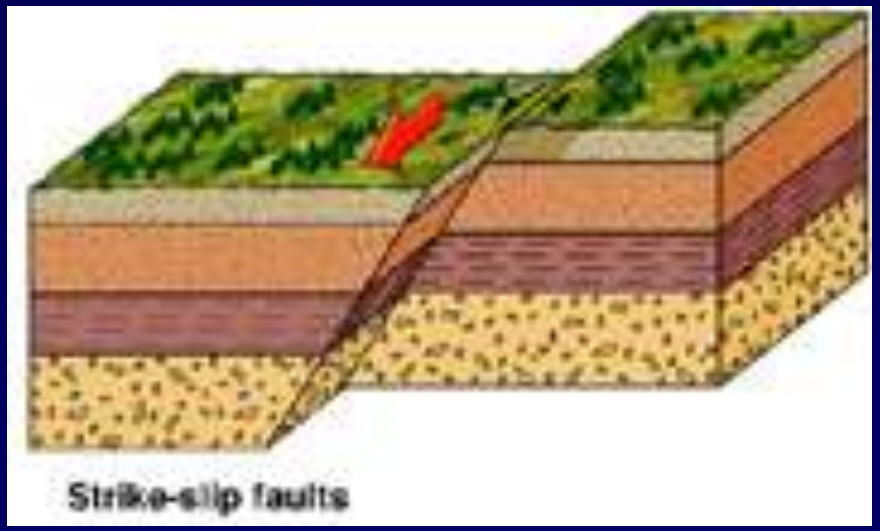


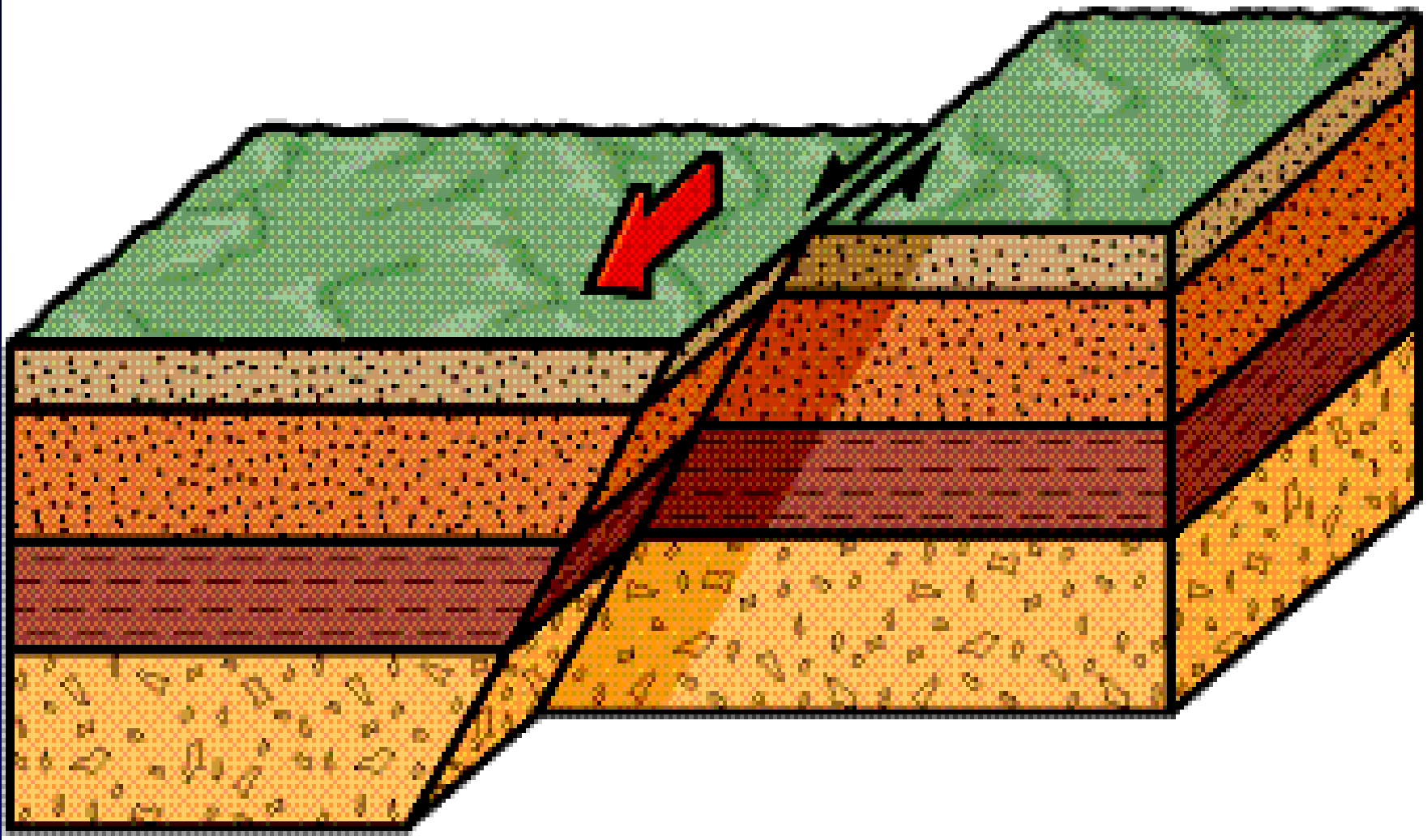

Thrust sheet
Thrust surface
d
c
b
a
b
c
d
d
c
b
a
50 km

Strike Slip Faults

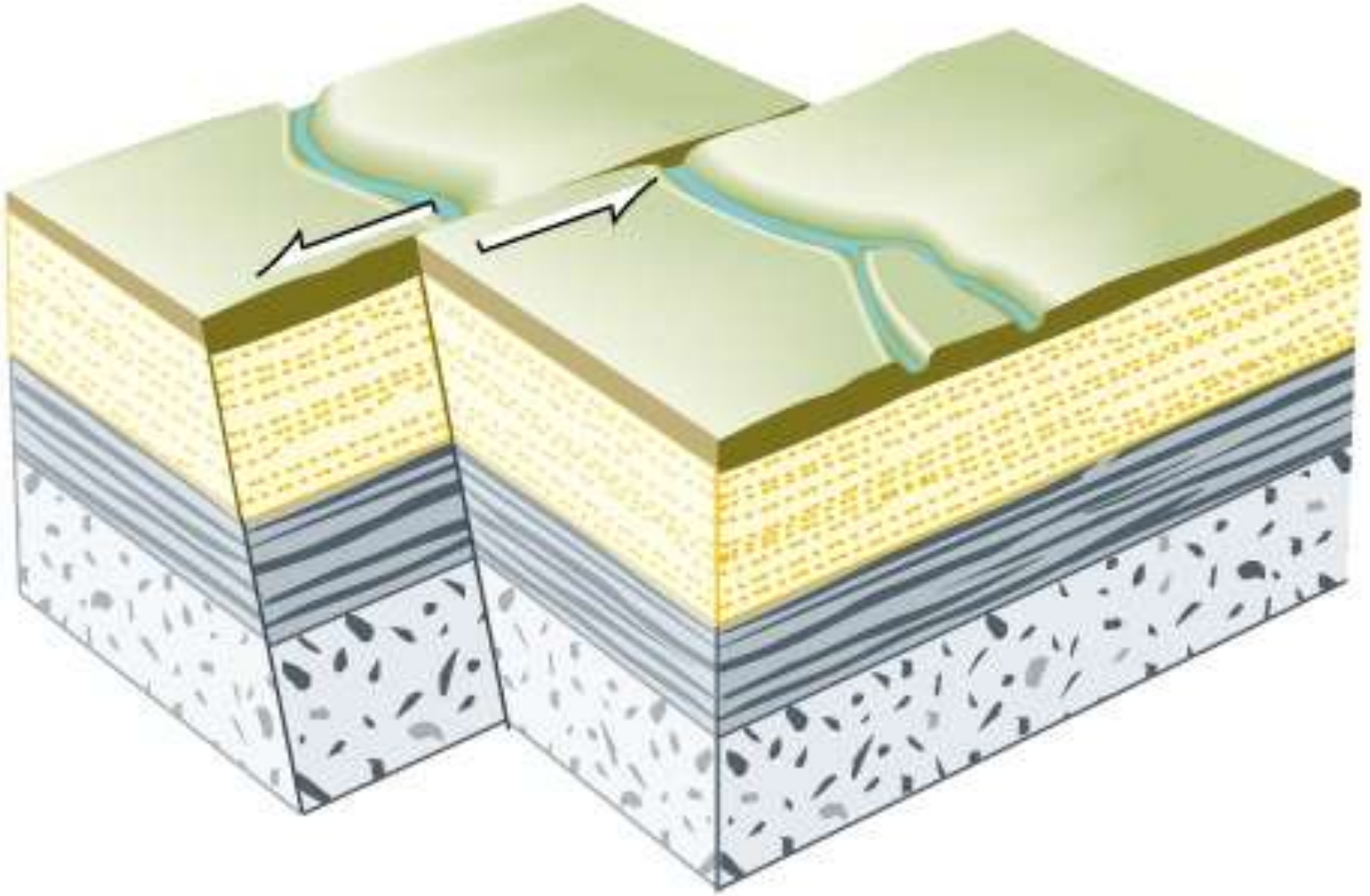
- ***Strike-slip faults*** have movement that is predominantly horizontal and parallel to the strike of the fault plane
  - A viewer looking across to the other side of a ***right-lateral*** strike-slip fault would observe it to be offset to their right
  - A viewer looking across to the other side of **a *left-lateral*** strike-slip fault would observe it to be offset to their left

Right-lateral San Andreas Fault





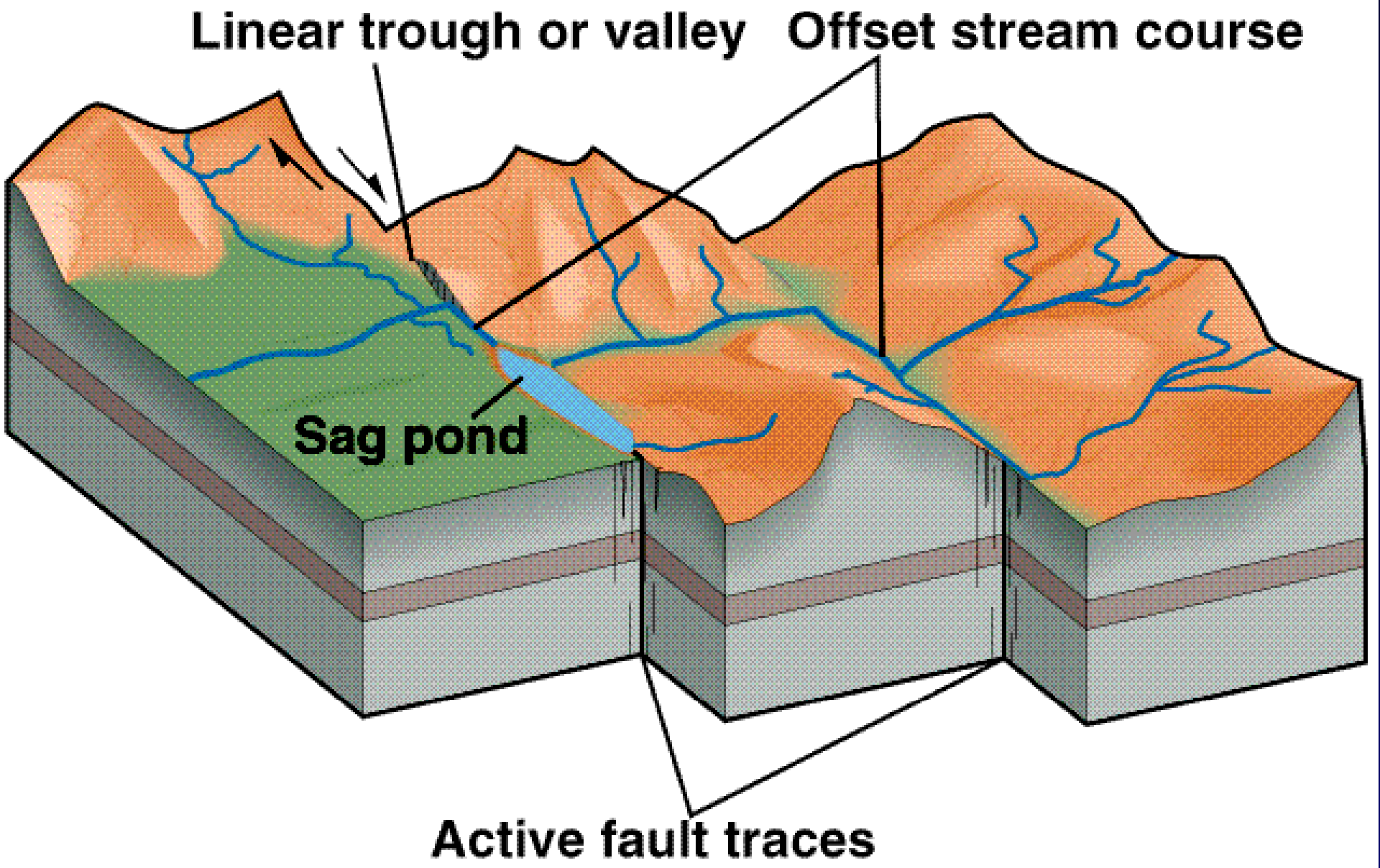
B Strike-slip faults



(c) STRIKE-SLIP FAULT
(left-lateral)

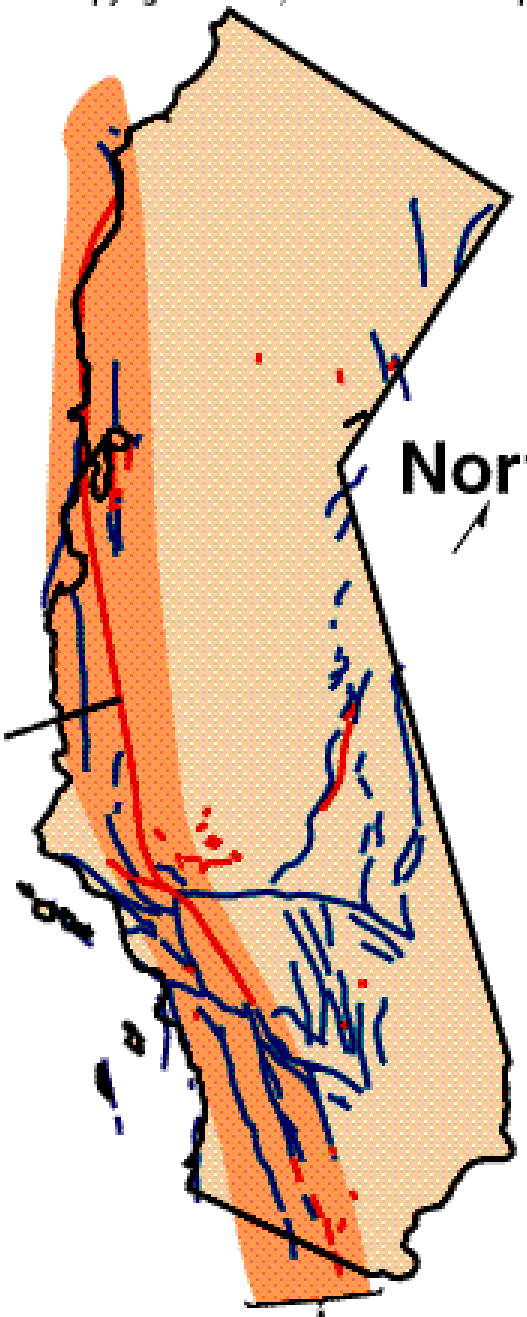

NORTH AMERICAN PLATE
San Andreas Fault
PACIFIC PLATE
Stream
Offset
Stream

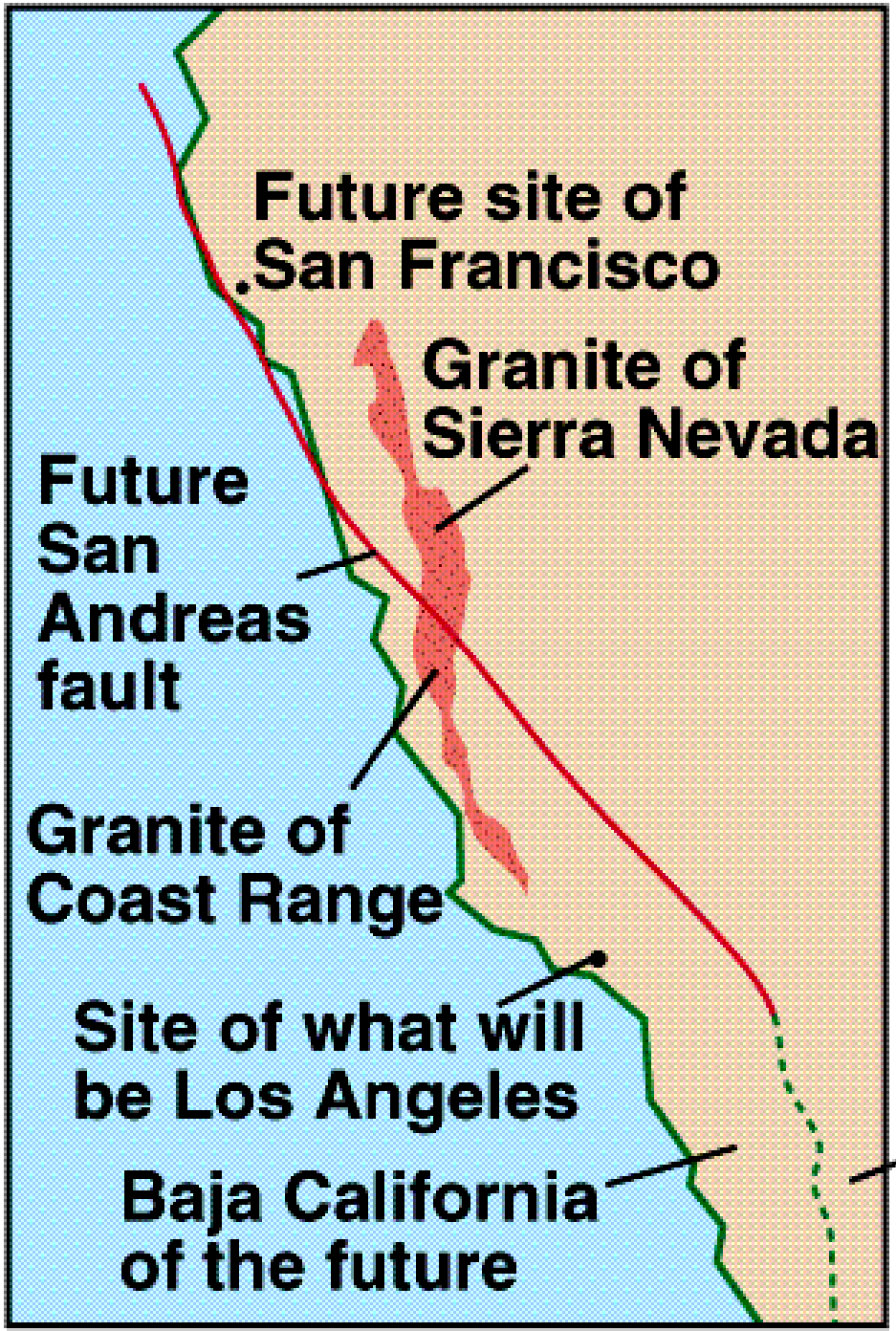
Right-Lateral Strike-Slip Fault



Stream Channel Displacement

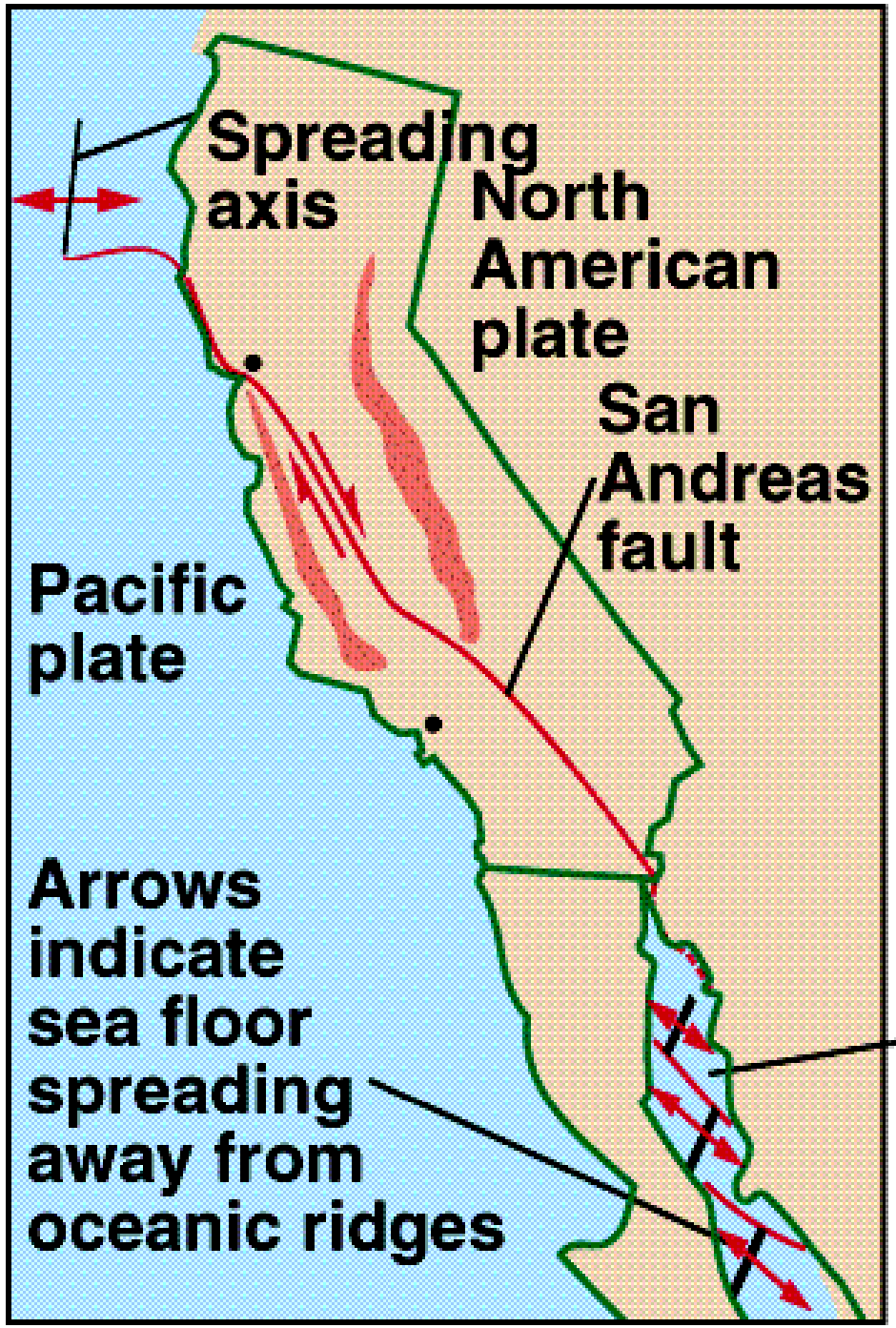
California Has Its Faults





CA and Mexico before Faulting

A



Motion Along San Andreas Fault

B

Structures as a Record of the Geologic Past

- Geologic maps and field methods
  - Observations of *outcrops*
  - Geologic map
  - Strike and dip

    Original horizontality

    Strike

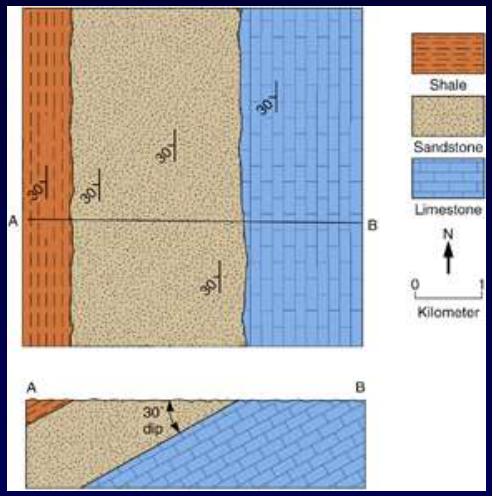
    Angle of dip

    Direction of dip

    Symbols
  - Geologic cross section

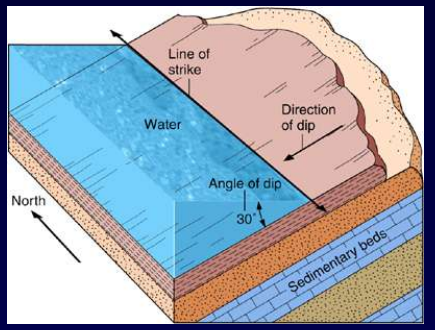
Structures and Geologic Maps

- Rock structures are determined on the ground by geologists observing rock *outcrops*
  - ***Outcrops*** are places where bedrock is exposed at the surface
- Geologic maps use standardized symbols and patterns to represent rock types and geologic structures, such **as *tilted beds*, *joints*, *faults* and *folds***



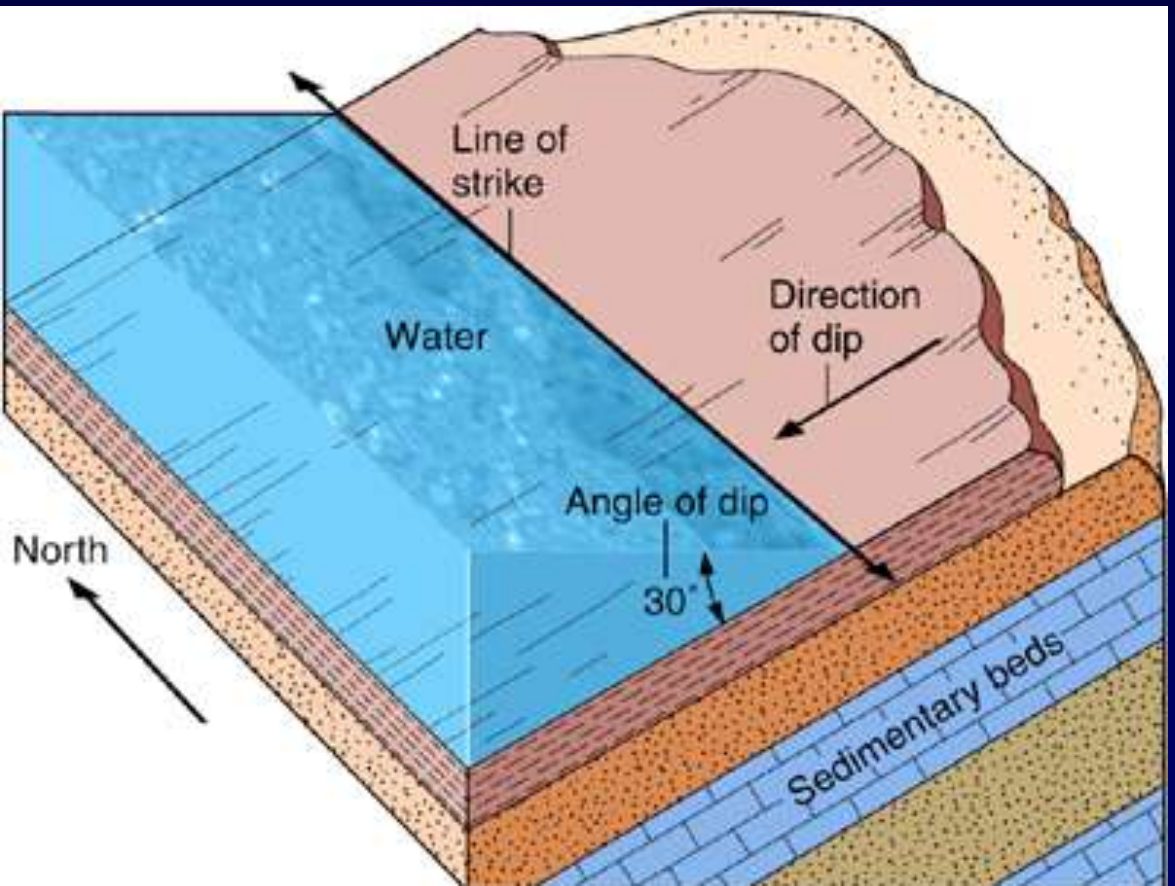
Orientation of Geologic Structures

- Geologic structures are most obvious in sedimentary rocks when stresses have altered their originally horizontal orientation
- *Tilted beds*, *joints*, and *faults* are planar features whose **orientation** is described by their ***strike* and *dip***

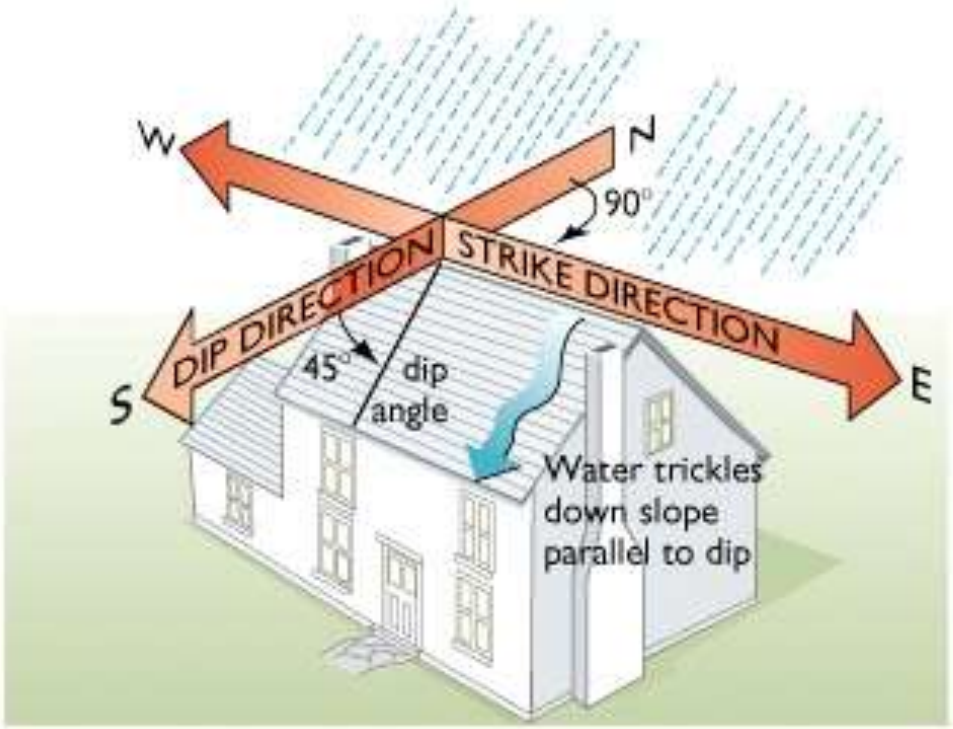


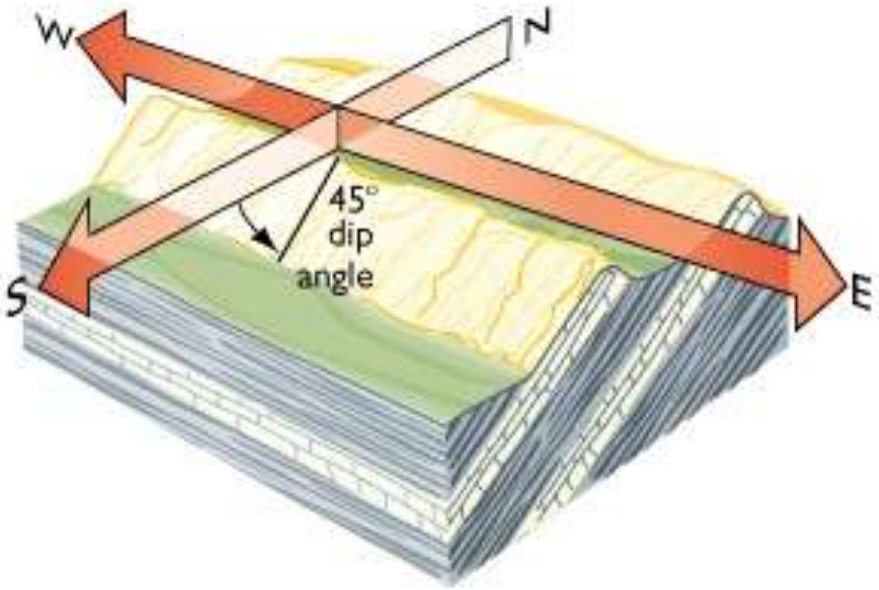
Strike & Dip

- ***Tilted beds*, *joints*, and *faults* are planar features whose orientation is described by their *strike* and *dip***
  - ***Strike* is the compass direction of a line formed by the intersection of an inclined plane with a horizontal plane**
  - ***Dip* is the direction in which and the angle downward from horizontal at which a plane is oriented**

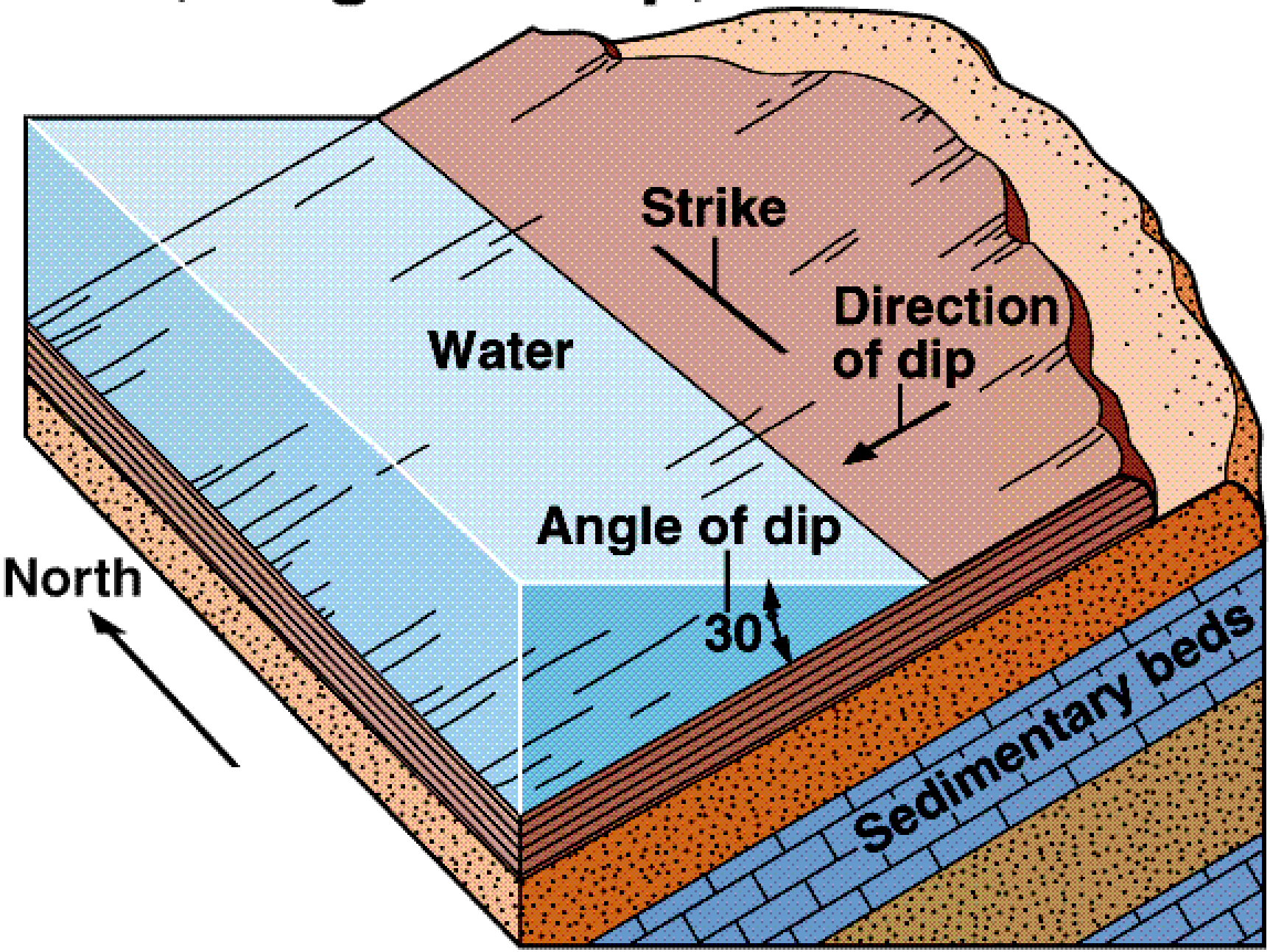


Attitudes and contacts — Keys to geologic maps and cross sections

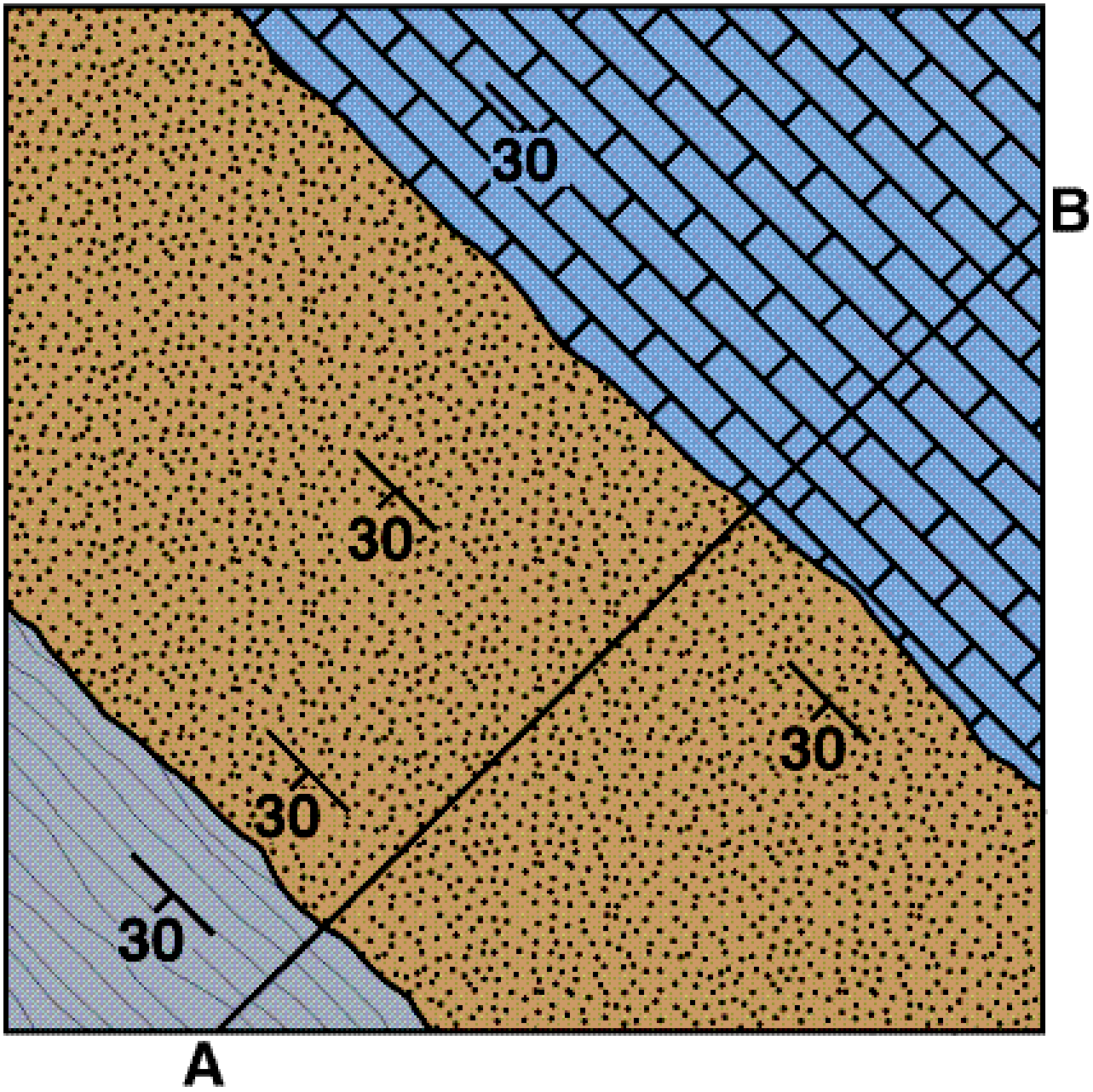


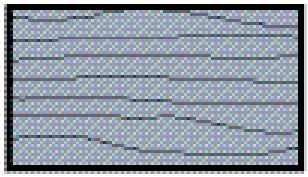


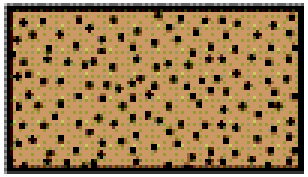
Strike; Angle of Dip; Direction of Dip

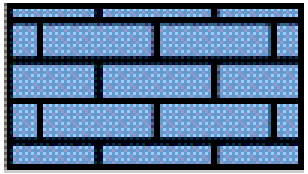


Geologic Map




Shale


Sandstone


Limestone

0 1

Kilometer

Deformation of Rocks — Physical

- Change in geometry, typically shapes
  - Commonly reflected in change in internal fabric
- Brittle — Ductile (— Elastic)
- Brittle phenomena — rocks break
  - Joints and faults
- Ductile phenomena — rocks flow (internal slip)
  - Folds and internal deformation (e.g., in metamorphism)

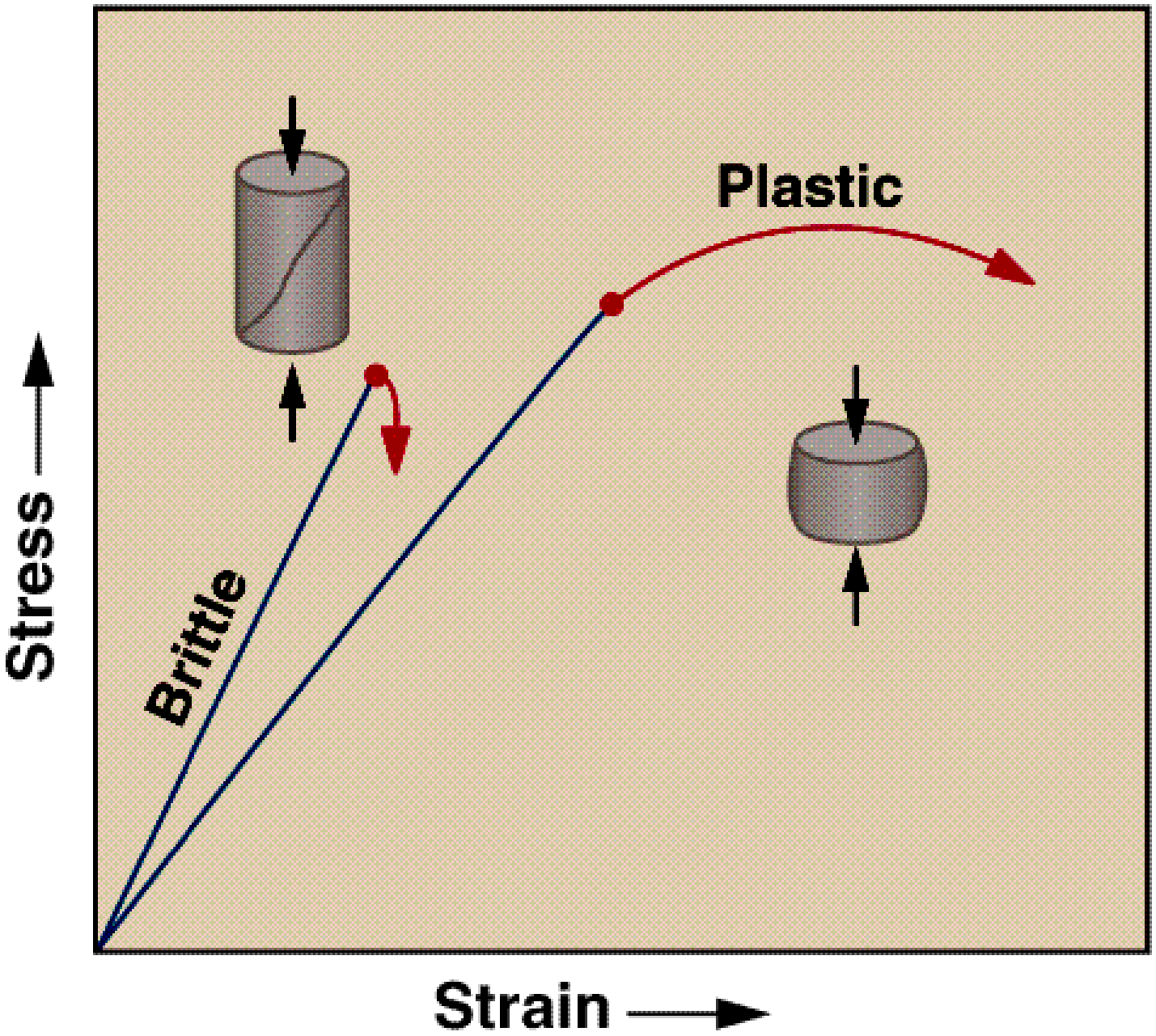
Brittle vs. Ductile Behavior

(a) (b) (c)

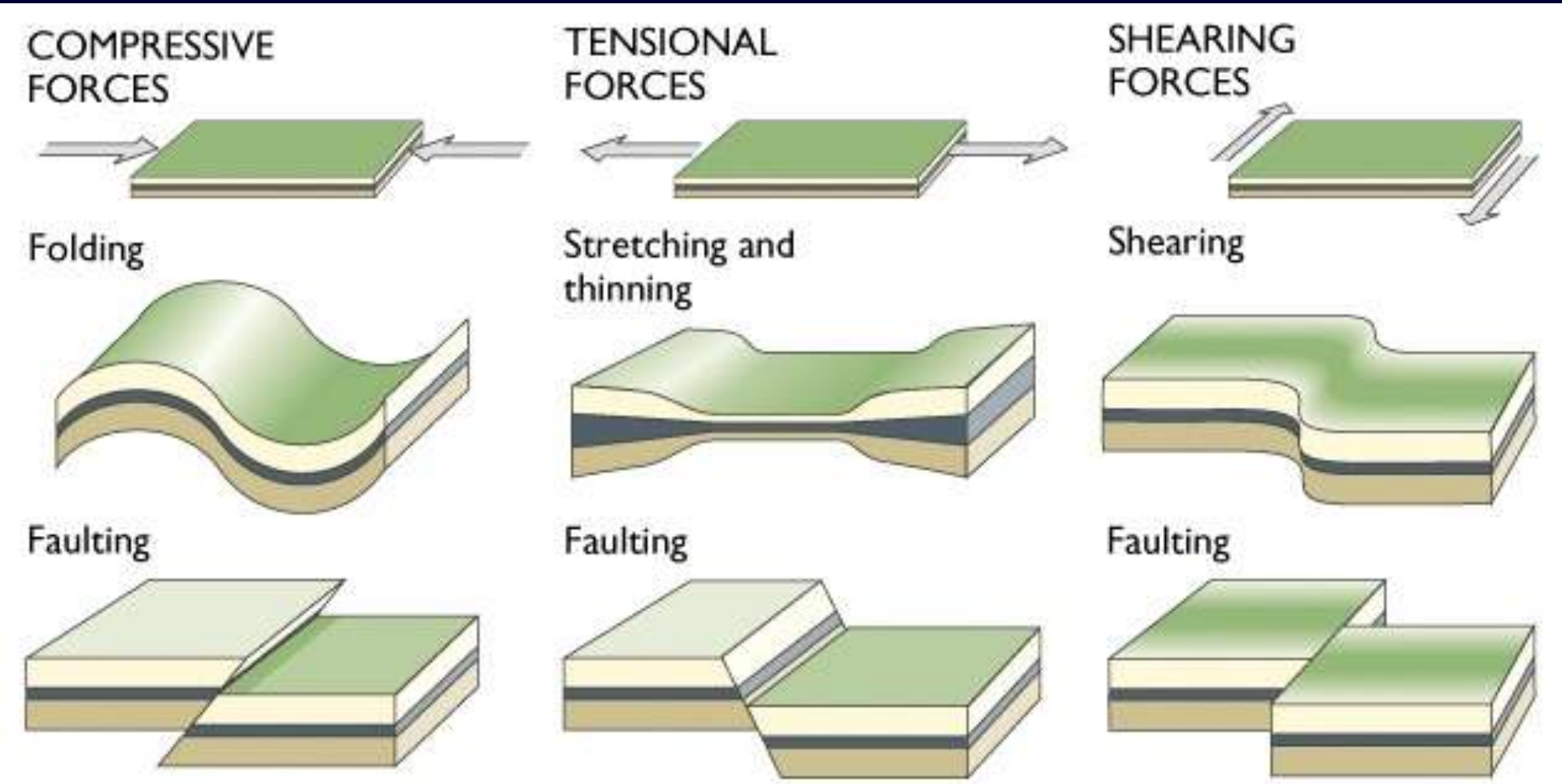
Records of strain (change in shape)

- Pre-existing features can serve as markers recording the changes in shape (if homogeneous strain)

Rock Behavior with Increased Stress



Structural styles with stress regimes



Geologic settings for deformation

- Compressional regimes — rocks under compression (e.g., many convergent margins); crustal thickening by folding, reverse & thrust faulting (Andes, Himalaya, Alps)

- Tensional regimes — rocks under extension— rifts, divergent margins, collapsing mountain belts — crustal thinning by normal faults, folding less common

- Strike-slip regimes — rocks subjected to shear, e.g., transform margins; no overall effect on crustal thickness, locally major extension or compression (southern California)

Summary

- Deformation of rocks over large volumes
  - Rocks break (fault) and flow (fold)
  - Driven by tectonics and gravity
  - Stress regimes: compression, tension, shear
  - Importance to geologic history and applications
- Attitudes of rocks: strike and dip
- Geologic maps and cross sections
- Types of folds
  - Anticlines (dip away)
  - Synclines (dip toward)
- Types of faults
  - Dip-slip: reverse (thrust, if low-angle) and normal
  - Strike-slip
  - Oblique-slip
- Styles reflect local to regional stress regimes

The End