1 **Crustal Deformation**

Earth, Chapter 10

2 ***Chapter 10 – Crustal Deformation***

3 **What Causes Rock to Deform?**

- Deformation is a general term that refers to all changes in the shape or position of a rock body in response to stress
  - Most occurs at or near plate boundaries
- Rock or geologic structures are the features that result from forces generated by the interactions of tectonic plates
  - *Folds*, *faults*, and *joints*
  - *Foliation* and *rock cleavage*

4 **What Causes Rock to Deform?**

5 **What Causes Rock to Deform?**

- Stress: The Force That Deforms Rocks
  - When stresses acting on a rock exceed its strength, the rock will deform by flowing, folding, fracturing, or faulting
  - The magnitude is a function of the amount of force applied to a given area
    - Uniformly in all directions = confining pressure
      - Does not change the shape or orientation of a rock body
    - Unequally in different directions = differential stress
      - Compressional
      - Tensional
      - Shear

6 **What Causes Rock to Deform?**

- Types of stress
  - Compressional stress squeezes a rock and shortens a rock body
  - Tensional stress pulls apart a rock unit and lengthens it
  - Shear stress produces a motion similar to slippage that occurs between individual playing cards when the top of the stack is moved relative to the bottom

7 **What Causes Rock to Deform?**

- Strain: A Change in Shape Caused by Stress
  - Strained bodies lose their original configuration during deformation

8 **How Do Rocks Deform?**

- Elastic, Brittle, and Ductile Deformation
  - Elastic deformation: The rock returns to nearly its original size and shape when the stress is removed
  - When stress is applied *gradually*, rocks *initially* respond by deforming elastically
  - Once the elastic limit (strength) of a rock is surpassed, it either bends (ductile deformation) or breaks (brittle deformation)

9 **Rocks Exhibiting Ductile Deformation**

10 **How Do Rocks Deform?**

- Factors That Affect Rock Strength
  - Temperature: Higher temperature rocks tend to deform by ductile deformation whereas cooler rocks tend to deform by brittle deformation
  - Confining pressure: Confining pressure squeezes rocks, making them stronger and harder to break—these tend to undergo ductile deformation

11 **How Do Rocks Deform?**

- Factors That Affect Rock Strength
  - Rock type:
    - Crystalline igneous and some metamorphic rocks, composed of minerals with strong chemical bonds generally experience brittle deformation

- Sedimentary and metamorphic rocks with zones of weakness generally experience ductile deformation
- Time: Forces applied gradually over a long period of time generally result in ductile deformation

12 **How Do Rocks Deform?**

- Ductile Versus Brittle Deformation and the Resulting Rock Structures
  - Most rocks exhibit brittle behavior in the upper 10 kilometers of the crust
    - *Joints* are cracks in the rocks resulting from the rock being stretched and pulled apart
    - *Faults* are fractures in the rocks where rocks on one side of the fault are displaced relative to the rocks on the other side of the fault
    - *Folds* are evidence that rocks can bend without breaking
      - Usually the result of deformation in high-temperature and pressure environments

13 **How Do Rocks Deform?**

14 **Folds: Rock Structures Formed by Ductile Deformation**

- Characteristics of folds
  - Most folds result from compressional stresses that result in a shortening and thickening of the crust
  - Each rock layer is bent around an imaginary axis: the *hinge line*
    - Hinge lines can be horizontal or inclined
  - The *axial plane* is a surface that connects all hinge lines of the folded strata

15 **Folds: Rock Structures Formed by Ductile Deformation**

16 **Folds: Rock Structures Formed by Ductile Deformation**

- Anticline and Synclines
  - Anticlines are upfolded or arched sedimentary layers
    - Oldest strata are in the center
  - Synclines are downfolded or troughs of rock layers
    - Youngest strata are in the center

17 **Folds: Rock Structures Formed by Ductile Deformation**

- Anticline and Synclines
  - Depending on their orientation, anticlines and synclines can be described as:
    - *Symmetrical*—the limbs of the fold are mirror images of each other
    - *Asymmetrical*—the limbs of the fold are not identical
      - Overturned (recumbent)—one or both limbs are tilted beyond vertical
      - Plunging—the axis of the fold penetrates the ground

18 **Common Types of Folds**

19 **Common Types of Folds**

20 **Plunging Anticline**

21 **Plunging Anticline**

22 **A horizontal (A) and plunging (B) anticline**

23 **Plunging Anticline**

24 **Plunging Anticline**

25 **A series of anticlines and synclines**

26 **Plunging anticlines and synclines**

27 ***Sheep Mountain anticline, Wyoming***

28 **Folds: Rock Structures Formed by Ductile Deformation**

- Domes and Basins
  - Domes are upwarped circular features
    - Oldest rocks are in the center
    - Can form due to intrusion of a laccolith
  - Basins are downwarped circular features
    - Youngest rocks are in the center

- Can form from subsidence of large sedimentary basins

29 **Domes Versus Basins**

30 **Domes Versus Basins (Black Hills vs Michigan)**

31 **Black Hills, South Dakota: a large dome**

32 **Folds: Rock Structures Formed by Ductile Deformation**

- Monoclines
  - Monoclines are large, step-like folds in otherwise horizontal sedimentary strata
    - Uniquely coupled with faults
    - As blocks of basement rocks are displaced upward, the ductile sedimentary strata drape over them

33 **The East Kaibab Monocline, Arizona**

34 ***My favorite monocline:***
(East Kaibab at Marble View)

35 **Image from WorldWind software:**
(predecessor of Google Earth)

36 **Topo map:**

37 **Faults and Joints: Rock Structures Formed by Brittle Deformation**

- Faults are fractures in rocks along which displacement has occurred
  - Sudden movements along faults are the cause of most earthquakes
- Fault orientation is described by strike and dip
  - Strike is the direction of a horizontal line on the inclined surface
  - Dip is the angle of inclination of that surface measured from the horizontal

38 **Faults and Joints: Rock Structures Formed by Brittle Deformation**

- Dip-Slip Faults
  - Dip-slip faults occur when movement is parallel to the inclination (dip)
    - The hanging wall is rock surface above the fault
    - The footwall is the rock surface below the fault
  - There are two general types of dip slip daults
    - Normal—hanging wall moves down
    - Reverse—hanging wall moves up

39 **Hanging Wall Block and Footwall Block**

40 **Hanging Wall Block and Footwall Block**

41 **Faults and Joints: Rock Structures Formed by Brittle Deformation**

- Normal faults are characterized by the hanging wall moving down relative to the footwall
  - Associated with tensional stress as the rocks pull apart, lengthening the crust
- Larger scale normal faults are associated with fault-block mountains
  - Example: Basin and Range Province
  - Uplifted blocks are called horsts
  - Down-dropped blocks are called grabens

42 **Faults and Joints: Rock Structures Formed by Brittle Deformation**

43 **Normal fault:**

44 **Normal Faulting in the Basin and Range Province**

45 **Faults and Joints: Rock Structures Formed by Brittle Deformation**

- Reverse faults are characterized by the hanging wall moving up relative to the footwall
  - Associated with compressional stress as the crust shortens
- Thrust faults have an angle less than 45º, so the overlying plate moves almost horizontally
  - Most pronounced along convergent plate boundaries
  - Example: Glacier National Park

46 **On a reverse fault, the hanging wall moves up relative to the footwall**

47 **Faults and Joints: Rock Structures Formed by Brittle Deformation**

48 **Faults and Joints: Rock Structures Formed by Brittle Deformation**

49 **Types of Dip-Slip Faults (summary)**

50 **Faults and Joints: Rock Structures Formed by Brittle Deformation**
- Strike-slip faults are characterized by displacement that is horizontal and parallel to the strike of the fault
  - Types of strike-slip faults
    - *Right-lateral*—As you face the fault, the opposite side of the fault moves to the right
    - *Left-lateral*—As you face the fault, the opposite side of the fault moves to the left

51 **Strike Slip Fault**

52 **Aerial View of a Strike Slip Fault**

53 **The Alpine Fault, New Zealand**

54 **Faults and Joints: Rock Structures Formed by Brittle Deformation**
- Strike-Slip Faults
  - Large strike-slip faults that cut through the crust to accommodate plate motion are called transform faults
  - Most continental transform faults consist of a zone of roughly parallel fractures
    - San Andreas Fault

55 **A block diagram showing the features along a strike-slip fault**

56 **The San Andreas fault system is a major transform fault**

57 **Faults and Joints: Rock Structures Formed by Brittle Deformation**
- Oblique-slip faults exhibit both a strike-slip and a dip-slip movement
- Joints are fractures in a rock where there has been no rock movement
  - Most joints appear in parallel groups

58 **Faults and Joints: Rock Structures Formed by Brittle Deformation**
- Oblique-slip faults exhibit both a strike-slip and a dip-slip movement

59 **Faults and Joints: Rock Structures Formed by Brittle Deformation**
- Faults and Earthquakes
  - Sudden displacement along a fault can produce an earthquake
  - Some of the most destructive earthquakes occur along strike-slip faults
    - Port-au-Prince, Haiti, 2010
  - Even larger earthquakes occur along low-angle thrust faults, called megathrust faults
    - Japan 2011, Sumatra 2004

60 **Faults and Joints: Rock Structures Formed by Brittle Deformation**

61 **Faults and Joints: Rock Structures Formed by Brittle Deformation**
- Fault Scarps
  - Vertical displacement along faults may produce long low cliffs called fault scarps

62 **Faults and Joints: Rock Structures Formed by Brittle Deformation**
- Slickensides
  - On some fault surfaces the rocks became highly polished and striated (grooved) as crustal blocks slid past each other
  - These surfaces are called slickensides

63 **Faults and Joints: Rock Structures Formed by Brittle Deformation**
- Joints are fractures in a rock where there has been no rock movement
  - One of the most common rock structures
  - Most joints appear in parallel groups
  - Produced when rocks in the outermost crust are deformed and experience brittle failure

64 **Parallel Joints**

65 **Mapping Geologic Structures**
- A geologist identifies and describes the dominant rock structures in a region
  - Using outcrops of exposed bedrock
  - Work is now aided by
    - Aerial photography

- Satellite imagery
- Global positioning systems (GPS)
- Seismic reflection profiling

66 **Mapping Geologic Structures**

- Strike and Dip
  - Sedimentary rocks that are inclined or bent indicate that the layers were deformed following deposition
    - Strike
      - The compass bearing of the line produced by the intersection of an inclined rock layer or fault with a horizontal plane
      - Generally expressed as an angle relative to north

67 **Mapping Geologic Structures**

- Strike and Dip
  - Dip
    - The angle of inclination of the surface of a rock unit or fault measured from a horizontal plane
    - Includes both an inclination and a direction toward which the rock is inclined
    - Always at a 90º to the strike

68 **Strike and Dip of Rock Layers**

69 **Strike and Dip of Rock Layers**

70 ***A geologic map illustrates the geologic structures of an area***

71 ***Strike and dip of a rock layer***

72 **Mapping Geologic Structures**

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