1 EVPP 110 Lecture
Fall 2002, Instructor: Dr. Largen
Earth Origin, Structure and Interplanetary Processes

2 Brief History of the Earth

- Origin of the universe
  - unknown for certain
  - still being actively researched
  - many different theories exist
    - Big Bang theory
    - inflation theory
    - cold dark matter theory
  - origin theories are difficult to test

3 Brief History of the Earth

- Age of the universe
  - unknown for certain
  - still being actively researched
  - several different methods exist for calculating age of universe, using
    - velocities and distances of galaxy clusters
    - information about stars & their life cycles
  - age estimates vary greatly by source
    - ranging from 8 billion to 14 billion years old

4 Brief History of the Earth

- origin and age of the universe
  - most “popular” origin theory
    - Big Bang Theory
  - most popular age estimate
    - ~ 12 billion years old
- diameter of the universe
  - thought to have been continually increasing since its creation
  - at present, ~ 2 x 10^{23} km

5 Brief History of the Earth

- universe is thought to have had a dynamic adolescence
  - from ~12 billion years ago (BYA) to ~7 BYA
    - galaxies, stars and planets of universe were formed, destroyed, re-formed
- birth of Earth
  - ~7 BYA
    - a red giant star in vicinity of present Earth catastrophically exploded (supernova)

    - ~4.6 BYA
        - remnants of that explosion form our solar system, including the Earth

6 The Earth in the context
of our solar system

7 Our solar system

- After collapse of red giant
    - a rotating, dense cloud (solar nebula) remained
        - as cloud cooled, it condensed and contracted
            - rotating faster
            - forming a flattened disk, thinnest at edges
        - as contraction continued, rings of material separated from the cloud
            - which in turn, condensed to form planets

8 Our solar system

- Resulting 9 planets can be grouped
    - terrestrial plants
    - Jovian (non-terrestrial) planets
    - Pluto

9 Our solar system

- terrestrial plants
    - because they are “earth-like”
        - rocky with metallic centers
            - heavier materials that stayed nearer sun
    - Mercury, Venus, Earth, Mars

10 Our solar system

- Jovian (non-terrestrial) planets
    - because they are similar to Jupiter
        - composed mostly of liquids and gases
            - lighter materials that boiled away from areas nearest to the sun
    - Jupiter, Saturn, Uranus, Neptune
- Pluto
    - anamolous; terrestrial but outer

11 The Earth In Context

12 Earth is unique in our solar system

- Why is the Earth so “special” relative to the other planets?
    - Temperature
    - presence & composition of atmosphere
    - water
    - continued tectonic activity

13 Age of the Earth

- 4.6 billion years old - current estimate
  - great age of the Earth has not always been known or agreed upon
- Greek philosophers
  - Earth ageless - no beginning or end to time
- Biblical scholar
  - Bishop Ussher (1664)
    - put age at 5,668 years
      - concluded Earth was formed on October 26, 4004 B.C, based on a literal translation of Bible

14 Early ideas about physical features of the Earth

- Throughout much of human history
  - was believed that major physical features of Earth were fixed and unchanging
    - continents, oceans, mountains, valleys were all in their “original” locations and would always remain in those locations, unchanged

15 Early ideas about physical features of the Earth

- Catastrophism
  - concept subscribed to by most natural sciences up through early 19th century
    - proposes that supernatural forces caused catastrophic events that re-shaped the physical landscape
      - Earthquakes
      - Volcanic eruptions
      - Floods

16 Early ideas about physical features of the Earth

- With rise of scientific thought and explorations
  - evidence against catastrophism grew over the centuries

17 Nicolaus Steno
(1638-1686)

- Formulated both the Principle of Superposition and Principle of Original Horizontality in 1669

18 Principle of Superposition

- Layers on bottom were deposited first, and are the oldest (A older than B, B older than C, etc.)
- In any unaltered sequence of rocks, oldest is at bottom, youngest at top

19 Principle of Original Horizontality

20 Principle of original horizontality

- Almost all strata are initially more nearly horizontal than vertical
- therefore, any strongly sloped stratum had to have been tilted by external forces after it was formed

21 Principle of Uniformitarianism
James Hutton (1726-1797)

- Geologic processes happening today operated in a similar fashion in the past, so provide guidance in studying the earth’s history

22 Uniformitarianism

- Principle of uniformitarianism
  - proposed by James Hutton in 1785
  - fundamental to modern science of geology
  - holds that laws of nature have not changed over time, were same in past as now
  - actualism
    - when we see ripples on ancient rock composed of hardened sand (sandstone)
      - we can assume that they developed in same way that similar ripples develop today
        - under influence of certain kinds of water movement or wind

23 Uniformitarianism

- Principle of uniformitarianism
  - James Hutton
    - believed that rocks of the past had formed as a result of the same processes that were currently operated at or near surface of the Earth
      - such as
        - volcanic activity
        - accumulation of grains of sand and clay under the influence of gravity

24 Uniformitarianism

25 Geologic Time
4,600,000,000 Years - Estimated Age of the Earth

26 Relative Dating

- Relative Age is the answers to a question like, “Which is younger?”
- Relative ages allow us to compare different geologic formations, and determine which is the oldest, next oldest, etc.

27 Principle of Cross-cutting Relationships – Dike

- A feature, such as a dike or fault, that cuts formations is younger than the formations it cuts

28 Principle of Cross-cutting Relation-ships
– Fault

- fault is younger than the beds it offsets

29 Principle of Inclusions

- Fragments of other rocks contained within the body of a rock are older than the rock

30 Sedimentary Conglomerate

- Rock fragments in this conglomerate are older than the conglomerate itself

31 Principle of Faunal Succession -
(proposed by William Smith (1769-1839))

- states that over time, organisms on earth have changed in a definite order that is reflected in fossil record
- Rocks with recently evolved life forms are younger than those with older forms

32 Index Fossils

- Organisms with specific characteristics:
  - Short lived (geologically)
  - Widespread occurrence
  - Readily recognized

33 Unconformities

- Gaps in the rock record
- mark boundaries between rocks of different ages
- may result from non-deposition (a hiatus), or from deposition followed by erosion

34 Unconformity in Volcanic Ash

- Outcrop photo of volcanic ash layers in Japan
- There is an erosional discontinuity (disconformity) that separates earlier folding in the lower half from folding (above) after later ash flows were deposited.

35 Nonconformity

- Boundary between unlayered igneous or metamorphic rocks, and overlying sequential sedimentary rocks
- Lower rocks show evidence of erosion before the deposition of the sedimentary rocks

36 Angular Unconformity

- Grand Canyon, Arizona

37 Geologic Correlation

- seeks to establish age relationships between distant sequences of rock
  - often through the use of fossil assemblages, or index fossils
- A key bed, a distinctive stratum that appears at several localities, may also be used

38 Absolute Age

- Determination of the absolute age is usually done using radiometric dating
- Absolute ages are expressed in years, or millions or billions of years, before present

39 Radiometric Dating

- Requires a parent isotope that undergoes radioactive decays to yield a daughter isotope at a known rate
  - Example:

- $^{14}C \rightarrow {}^{14}N$
- Radioactive decay follows an exponential decay law

40 Radiometric Decay

41 Half-life, $t_{1/2}$

- time necessary for half of original atoms of parent isotope to decay into daughter isotope

42 Parent and Daughter Isotopes

- In the previous example,
  - $^{14}C \rightarrow {}^{14}N$
- ^{14}C is the parent, and ^{14}N is the daughter
- The half-life, $t_{1/2}$, is 5730 years

43 Geologic Time Scale

- Eons
  - largest divisions of time, beginning with the Archean (4.6 to 3.8 billion years ago)
  - Eras (subdivisions of eons)
    - defined by dominant life forms
    - Periods (divisions of eras)
      - based on smaller scale changes
      - Epochs (divisions of periods)
        - based on detailed, smaller scale changes

44 Geologic Time Scale

- Archean Eon (4.6bya-2.5bya)
- Proterozoic Eon (2.5bya-543mya)
- Phanerozoic Eon (543mya-present) “interval of well-displayed life”
  - Paleozoic Era (543mya-251mya) “old life”
    - 8 periods; Cambrian, Ordovician, Silurian, Devonian, Mississippian, Pennsylvania, Permian
  - Mesozoic Era (251mya-65mya) “middle life”
    - 3 periods; Triassic, Jurassic, Cretaceous
  - Cenozoic Era (65mya-present) “modern life”
    - Paleogene Period (65mya-24mya)
      - 3 epochs; Paleocene, Eocene, Oligocene
    - Neogene Period (24mya-present)
      - 4 epochs; Miocene, Pliocene, Pleistocene, Holocene

45 Geologic Time

46 Paleozoic Era (543mya-251mya)

- Trilobite fossil, early Paleozoic era

47 Mesozoic Era (251mya-65mya)

- “age of the dinosaurs”
- Dinosaurs were dominant life forms

48 Cenozoic Era (65mya-present)
- “age of mammals”
- Kangaroos are marsupials, a type of mammal

49 Components of the Earth System - or “Ecospehre”
50 Components of the Earth System
51 Components of the Earth System
- Ecosphere
  - entire earth system
  - includes all other spheres
- Lithosphere
  - solid earth, including earth’s crust & part of upper mantle
- Hydrosphere
  - liquid envelope of water which surrounds our planet
- Atmosphere
  - layer of gas (air) which surrounds our planet
- Biosphere
  - living organisms which inhabit all of above spheres.

52 Interior Structure of Earth
53 Earth’s Structure
- “Layman’s” description
  - hot, dense, solid inner iron core
  - hot, dense, molten iron outer core
  - thick, rocky mantle
  - thin, rocky crust
- Two ways typically used to formally describe Earth’s structure
  - chemical-based description
  - mechanical-based

54 Earth’s Structure
- chemical-based description
  - Crust
  - Mantle
  - Core

55 Crust
- outermost layer or shell of the Earth
- represents <0.1% of Earth's total volume
- total depth is ~100km
- floats on upper mantle
- is broken into 16 plates

56 Crust
- Nine elements compose ~99% of mass of Earth’s crust

- oxygen = 45%
- silicon = 27%
- aluminum = 8%
- iron = 5.8%
- calcium = 5.1%
- magnesium = 2.8%
- sodium = 2.3%

57 Crust

- can be divided into
  - continental
    - 30-60km thick
    - composed of Al, Ca, K-rich silicate (“granite”)
    - density ~2.8 g/cm^3
  - oceanic
    - 6-10km thick
    - Fe, Mg-rich silicate (“basalt”)
    - density ~3.0 g/cm^3

58 Mantle

- zone of Earth below crust & above core
- ~3000km thick
- consists of soft rock, mostly Fe, Mg-rich silicates
- density ~3.2-5.0 g/cm^3
- constitutes ~ 67% of Earth’s mass
- can be divided into
  - upper mantle
  - transition zone
  - lower mantle

59 Core

- central zone Earth's interior
- ~3000km thick
- composed of metallic iron
  - no silicate
- density ~10 g/cm^3
- can be divided into
  - inner core
  - transition zone
  - outer core

60 Interior Of The Earth

61 Earth’s Structure

- Mechanical-based description

- Lithosphere
- Asthenosphere
- Mesosphere
- Outer Core
- Inner Core

62 Lithosphere

- solid portion of Earth
  - as compared with atmosphere & hydrosphere
- includes crust & part of upper mantle
- ~100 km thick
- rigid
- very strong, rigid
- cool

63 Asthenosphere

- layer or shell of Earth below lithosphere
- plastic - but solid
- very weak
- hot
- ~200km thick
- is part of upper mantle

64 Mesosphere

- layer or shell of Earth below asthenosphere
- plastic
- weak, but stronger than asthenosphere
- hot
- ~2600km thick
- is remainder mantle

65 Outer Core

- Molten
  - iron, nickel, dissolved sulfur and oxygen
- constitutes ~30% of Earth's mass
- ~2200km thick
- convection currents in this region generate Earth's magnetic field

66 Inner Core

- solid
  - mostly iron, some nickel
- ~1400km thick
- constitutes ~2% of Earth's mass

- floats in middle of molten outer core
- pressure reaches ~3 million atmospheres
- temperatures range from 4000-5000°C

67 The Earth Is a Differentiated Planet - It Has Layers

68 Interior of Earth
- is hot and dense
  - weight of upper layers presses on interior
  - extreme compression leads to extreme heating
  - results in extremely hot and compressed deep interior
- since metals are heavy and rocks are light
  - heavy metals sink to center (iron and nickel)
  - lighter minerals float to surface (silicates)

69 Interior of Earth
- temperature
  - increases nonlinearly with depth
- pressure
  - increases linearly with depth
- density
  - increases with depth
- combination of temperature and pressure determines when materials in Earth will be molten versus solid
- also affects production of convection process in asthenosphere

70 Isostasy
- condition of equilibrium, comparable to floating, of units of lithosphere above asthenosphere
- Crustal loading, as by ice, water, sediments, or volcanic flows, leads to isostatic depression or downwarping
- Crustal unloading, as by erosion, or melting of ice, to isostatic uplift or upwarping

71 Plate Tectonics

72 Theory of plate tectonics
- Based on 6 lines of evidence
  - shapes of continents and continental shelfs
  - similarities

73 Alfred Wegener, 1880-1930

Wrote The Origin of Continents and Oceans in 1915

74 Continental Drift
- 550 MYBP

75 Fossil Plant Evidence
Glossopteris
- Extinct group of seed plants that arose during the Permian on the great southern

continent of Gondwana

76 Lithologic (Rock) Evidence

77 How Can a Continent Move?

- The biggest objection was the lack of a mechanism for moving continents
- Wegener spent the rest of his life looking for evidence to support his ideas
- He died in Greenland in 1930, while seeking more evidence

78 Convection Cell

- Heat beaker
- Water expands and rises
- It spreads and cools at the top
- Cool water sinks

79 Asthenosphere

80 Oceanographic Exploration

81 Sea-floor Spreading

- Concept came from oceanographic investigations
- Uses Convection cells, an idea Wegener would have been familiar with

82 Puzzles Solved

- Why is there so little sediment on ocean floor?
- What are the rock ages so young?

83 Age of Ocean Fossils

- Continental fossils are at least 3.5 billion years old
- Oldest marine fossils are about 180 million years
- Since life is though to originate in the oceans, why aren't ocean fossils older?

84 Seismic Evidence

85 Subduction Zones

The key to subduction is the density of the rock types involved

Density = mass/unit volume

86 Rock Densities

- Continental lithosphere is about 3.00 grams/cubic centimeter
- Oceanic lithosphere gradually increases in density as it ages, reaching a maximum value of about 3.28 grams/cubic centimeter

87 Converging Plates

- When two plates collide, the denser plate will sink (subside) beneath the less dense plate

- Density differences as small as 1% are enough to cause subduction

88 Asthenosphere Density
- density of the asthenosphere is about 3.3 g/cm^3
- Density increases with depth below the surface

89 Plate Movement
- Plates move slowly (up to 15 cm/yr)
- Plates may collide, move apart, or slide past each other
- Friction during plate movement often generates earthquakes

90 Plate Tectonics and Oceans

91 Subduction Zones
- Plots of earthquake foci over time delineate position of subducting plates
- plate which is subducted is always denser than plate which remains on surface

92 Subduction Angle
- Plates far from the spreading center will be relatively cold, and therefore dense –
  - they will subduct at a steep angle
- Plates near the spreading center will be much warmer
  - they will be only slightly denser than surface plate, and the subduction angle will be shallow

93 Oceanic Trenches
- Subducting plate drags part of the surface with it
- Creates large oceanic trenches, which also serve to mark the top of the subduction zones

94 Volcanic Arcs
- Plates subducted under continents create long chains of volcanoes on the continents
  - Cascades and Andes are examples
- Plates subducted under oceanic plates create chains of oceanic islands
  - Japan, the Philippines, and Indonesia are examples

95 Plate Motions
- movement relative to each other
  - Convergent
    - plates move toward each other, often a head-on collision
  - Divergent
    - plates move away from each other
  - Transform
    - plates move past each other along transform faults

96 Plate Types
- At any given point, a plate is either oceanic or continental
- Interactions between plates are thus:
  - Ocean-ocean (O-O)

- Ocean-continent (O-C)
- Continent-continent (C-C)

97 Hydrothermal Vents

- Spreading centers are marked by vents which spew hydrothermal fluids as hot as 350°C
- Fluids contain dissolved metals which precipitate when they hit cold ocean water, encrusting basalt - vents are called "black smokers" for this reason

98 Earth's Magnetic Field

- Earth has a strong magnetic field
- It is dipolar, with the poles being called north and south

99 Earth's Magnetic Polarity

- Present north magnetic pole is located near the south geographic pole
- South magnetic pole is located near the north geographic pole

100 Rock Magnetism

- Rocks often become magnetized because magnetic mineral grains (usually magnetite) are aligned
- Rock's magnetic field is fixed at the time magma cools for igneous rocks, or at the time of lithification for sedimentary rocks
- Magnetism of older rocks is called "paleomagnetism"

101 Magnetic Stripes

- In the early 1960's oceanographic research uncovered a curious phenomenon, called magnetic stripes
- Measurements of the earth's magnetic field show small variations from place to place

102 Magnetic Anomalies

- Magnetic Anomaly = Average regional magnetic field of the earth - magnetic field at a point
- Plotting magnetic anomalies lead to a curious pattern of "stripes", first seen in the Atlantic, later in the Pacific

103

- Sea-floor spreading
  - new magma emerging at a mid-ocean ridge and hardening into rock, which then spread away from the ridge with time
- Polarity reversals
  - North and South magnetic poles changing position suddenly

104

- If we assume sea-floor spreading is occurring, the magnetic field of the rock is fixed, in alignment with the earth's field, at the time the rock cools
- The measured field above such rocks equals the earth's field plus the rock's field (because they are aligned)

105 Magnetic Stripes

- As magma rises, it hardens and its magnetic field matches the present field of the earth - after a polarity reversal, it will be aligned against the earth's field

106 Hot Spots

- generate magma in the asthenosphere
  - below moving lithospheric plates
  - may be used as a reference since they are effectively stationary relative to lithospheric plate
- produce volcanoes
  - like Hawaiian Islands or many seamounts or guyots (mountains that made it above sea-level, then were flattened by wave erosion)

107 Earthquakes and The Earth’s Interior

108 Earthquake

- A sudden motion or trembling in the Earth caused by the abrupt release of slowly accumulated strain
- Strain is a change in the shape or volume of a body as a result of stress

109 Focus

- initial rupture point of an earthquake
  - where strain energy is first converted to elastic wave energy
- point within Earth which is center of an earthquake

110 Epicenter

- The point on the Earth's surface that is directly above the focus of an earthquake

111 Seismograph

- An instrument that detects, magnifies, and records vibrations of Earth, especially earthquakes
- resulting record is a seismogram

112 Example Seismogram

- Seismogram showing an earthquake - the three different traces represent vibrations in different directions
- First peaks are P waves, the second peaks the S waves

113 Richter Scale

- Numerical scale of earthquake magnitude
- Devised in 1935 by the seismologist C.F. Richter
- Defined local magnitude as the logarithm, to the base 10, of the amplitude in microns of the largest trace deflection that would be observed on a standard torsion seismograph at a distance of 100 km from the epicenter

114 Richter Scale Continued

- Measures vibrational amplitude of earth in response to seismic waves
- Does NOT measure energy release

115 Mercalli Scale

- Arbitrary scale of earthquake intensity, ranging from I (detectable only instrumentally) to XII (causing almost total destruction)
- Based on human perception of the earthquake, and damage observed after the

earthquake is over

116 Number of Earthquakes/Year

117 Energy Released by Earthquakes

- A great earthquake releases the equivalent of 1 billion tons of TNT or more, over a period of 1-2 minutes
- Most intense energy release per unit time of any natural event

118 Depth of Focus

- Earthquakes are classified by the depths of their foci below the surface, as follows:
  - Shallow 0-70 kilometers
  - Intermediate 70-300 kilometers
  - Deep 300-700$^+$ kilometers

119 Earthquake Damage

- Earthquakes can cause damage in a number of ways
  - Building Collapse
  - Tsunami waves
  - Seiche waves
  - Landslides
  - Liquefaction
  - Fire
  - Disease

120 Tsunami

- Gravitational sea wave produced by any large-scale, short-duration disturbance of the ocean floor
- Disturbances caused principally by a shallow submarine earthquake, but also by submarine earth movement, subsidence, or volcanic eruption

121 Seiche

- Free or standing-wave oscillation of the surface of water in an enclosed or semi-enclosed basin (as a lake, bay, or harbor)

122 Landslides

- Earthquakes may trigger mass movement of rock and sediment on unstable slopes
- Damage is most likely to occur after fire removes vegetation, or clear-cutting of forests

123 Liquefaction

- Liquefaction is a physical process that takes place during some earthquakes that may lead to ground failure
- As a consequence of liquefaction, soft, young, water-saturated, well sorted, fine grain sands and silts behave as viscous fluids rather than solids

124 Fire

- Fire often does more damage than the earthquake itself
  - Underground pipelines and tanks rupture

- Above ground tanks may rupture or tip over, spilling contents
- Water lines break
- Streets are blocked by debris
- Downed electrical lines may spark, setting off fires

125 Disease

- Earthquakes can cut underground sewer and water lines
- No drinking water
- Only available water is contaminated

126 Volcanoes and Volcanism

127 Volcano

- A vent in the surface of the Earth through which magma and associated gases and ash erupt
- Also, the form or structure, usually conical, that is produced by the ejected material
- Plural: volcanoes
- Etymology: the Roman deity of fire, Vulcan

128 Pyroclastic Eruptions

- Magma spews upward with great force through a central vent

129 Fissure Eruptions

- Volcanic eruptions may occur much more quietly along long cracks in the ground

130 Effect on Climate

- Large volcanic eruptions can block a great deal of the sun's energy from reaching the earth's surface
- This cools the climate until the tephra particles sink to the surface

131 Krakatau Volcano

- Located in the Sunda strait between the islands of Java and Sumatra

132 Krakatau, 1883 Eruption

133 Nuée Ardente

- A swiftly flowing, turbulent gaseous cloud, sometimes incandescent, erupted from a volcano and containing ash and other pyroclastics in its lower part; a density current of pyroclastic flow
- Etymology: French, "glowing cloud"

134 Prediction of Volcanic Eruptions

- Man cannot stop subduction, or magma generation - therefore, the prediction of imminent eruption becomes very important