Riches in Rock: Energy and Mineral Resources

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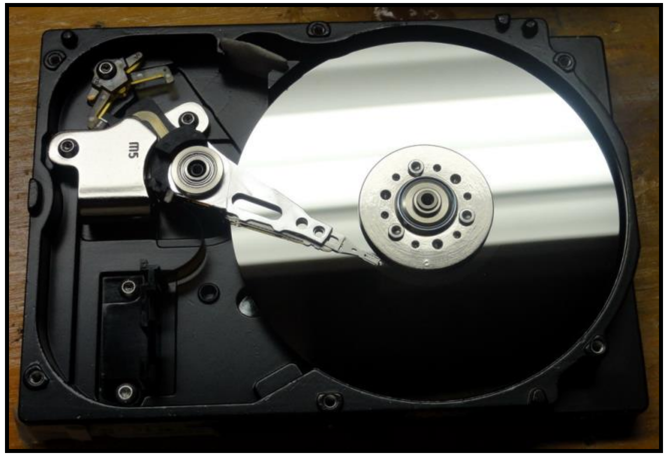
Energy & Mineral Resources

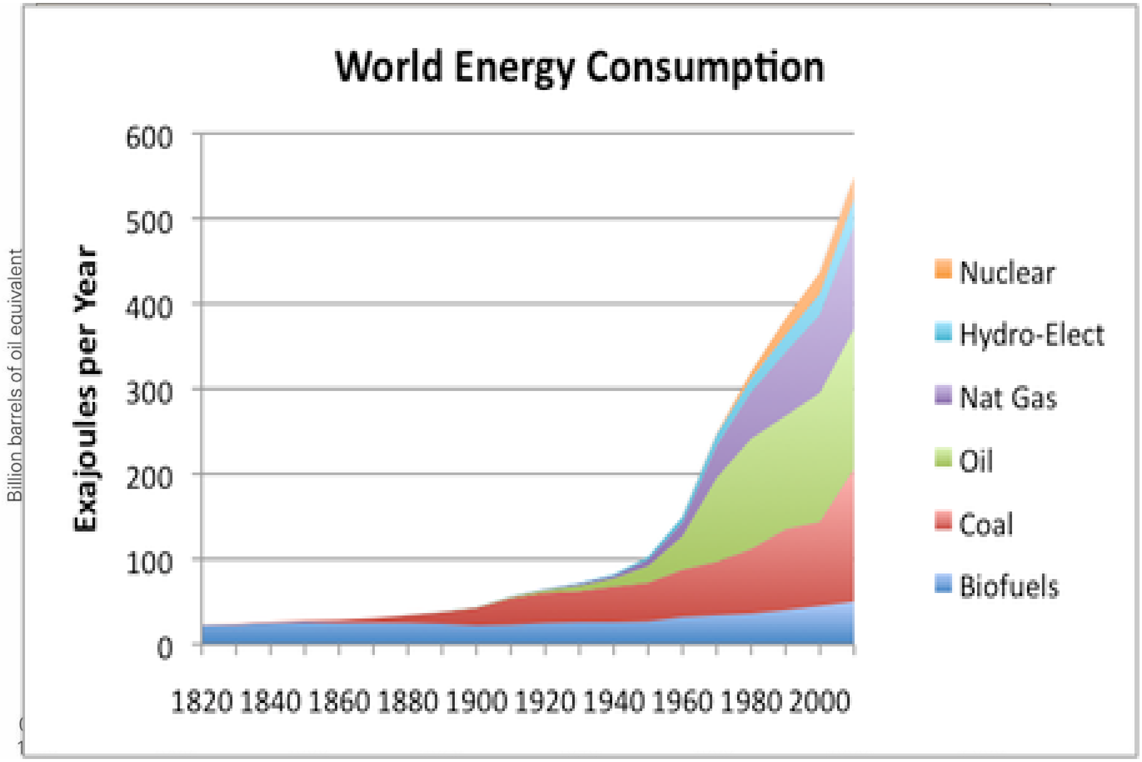
- Most energy and mineral resources are:
  - Geologic materials
  - Originate from geologic processes
- Important to understand:
  - How do energy and mineral resources form?
  - Why do they occur where they do?
  - How are they be extracted and processed?
  - How does extraction and use impact the environment?



Energy Resources

- Human energy consumption has grown steadily.
- People in industrialized countries today consume over 100 times more resources than pre-industrial times.

  - Population has tripled in the past 70 years
  - Material prosperity depends directly on energy use
  - Use of fossil and nuclear fuels has increased by more than a factor of 5
  - Global use > 10^8 barrels (159 l) per day

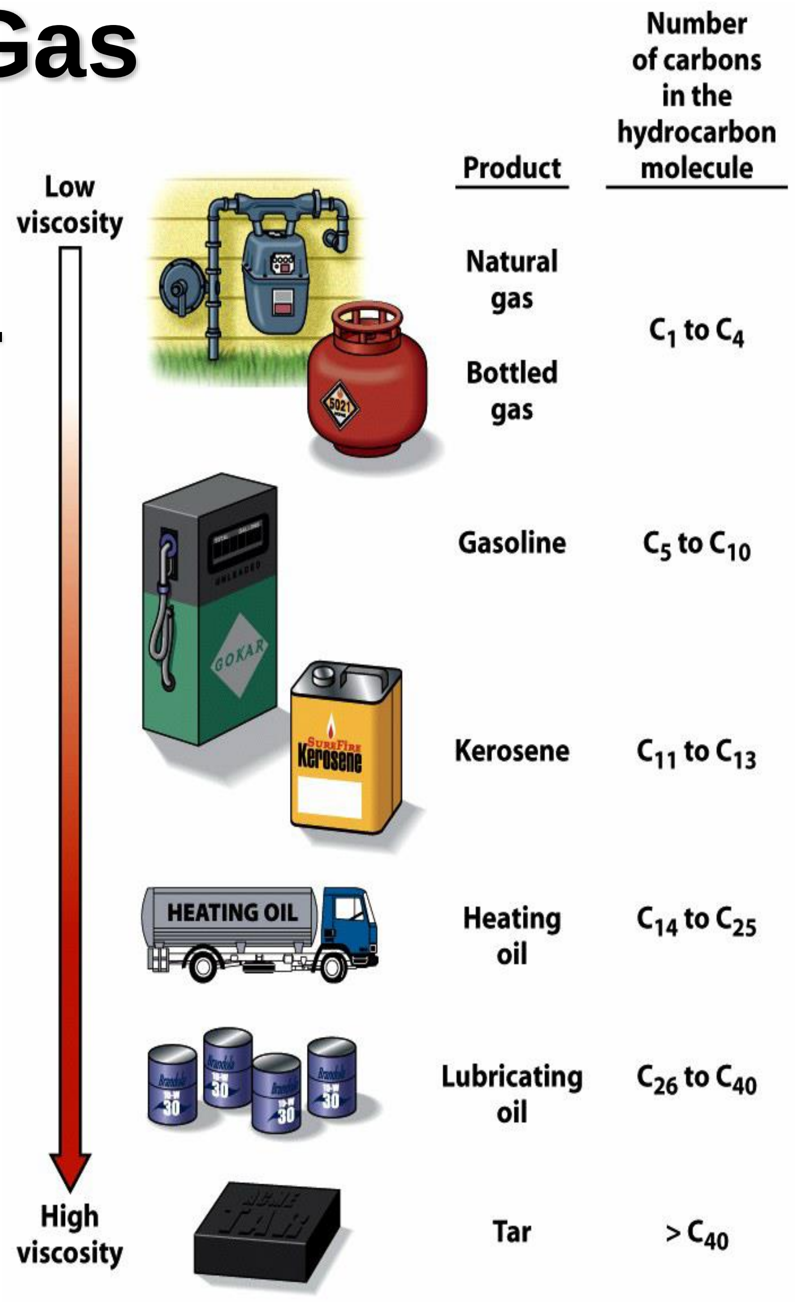


Sources of Energy

- Energy is the capacity to do work.
- Seven fundamental sources of energy:
  - Energy directly from the Sun
  - Energy directly from gravity (hydroelectric generation)
  - Energy via photosynthesis
  - Energy from chemical reactions
  - Energy from nuclear fission
  - Energy from Earth’s internal heat

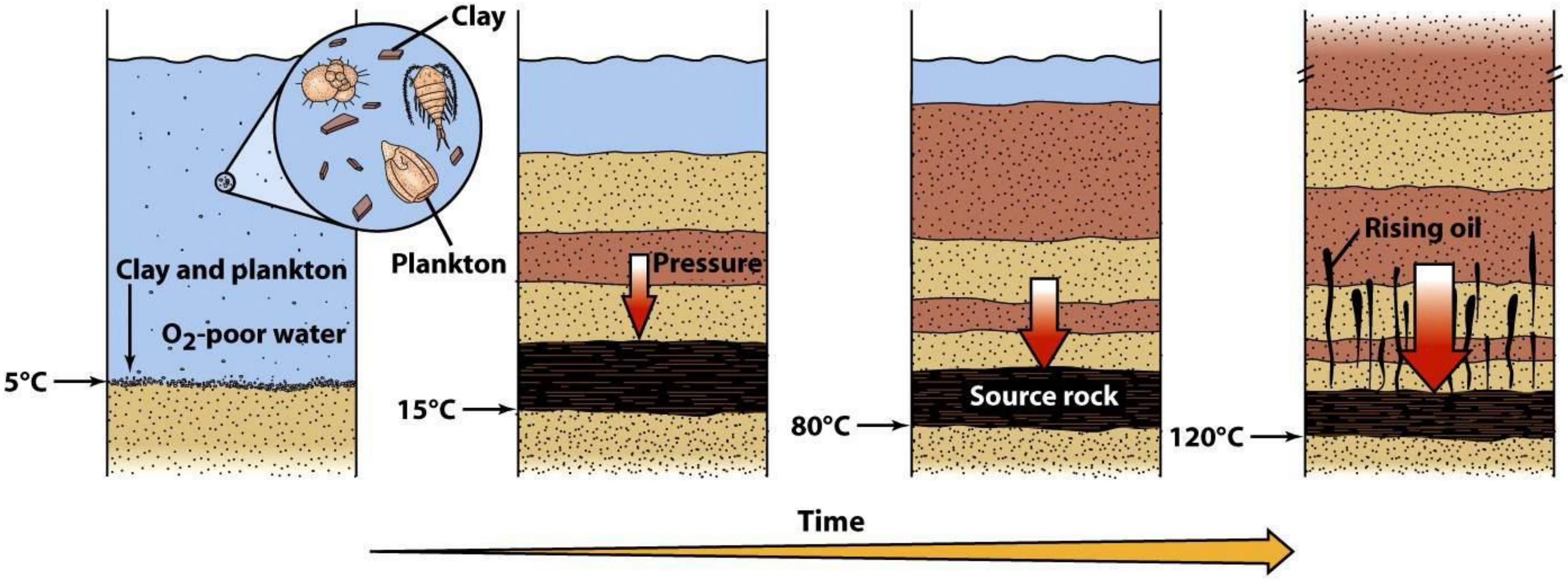
Oil and Gas

- Industrial society depends on oil (petroleum) and natural gas.
- Oil and gas are hydrocarbons:
  - Complex organic molecules
  - Chains or rings of C and H
- Size of molecule determines
  - Viscosity (ability to flow)
  - Volatility (ability to evaporate)
- Short chains are gases.
- Moderate-length chains are liquids (gasoline and oil).
- Long chains are solids (tar).



Oil and Gas Genesis

- Hydrocarbons originate from lipids (fatty molecules).
  - Plankton die and sink to floor of sea or lake.
  - This organic material accumulates offshore as fine mud.
  - Under anoxic conditions, organic material is preserved.
  - Lithification forms black shale, a petroleum source rock.

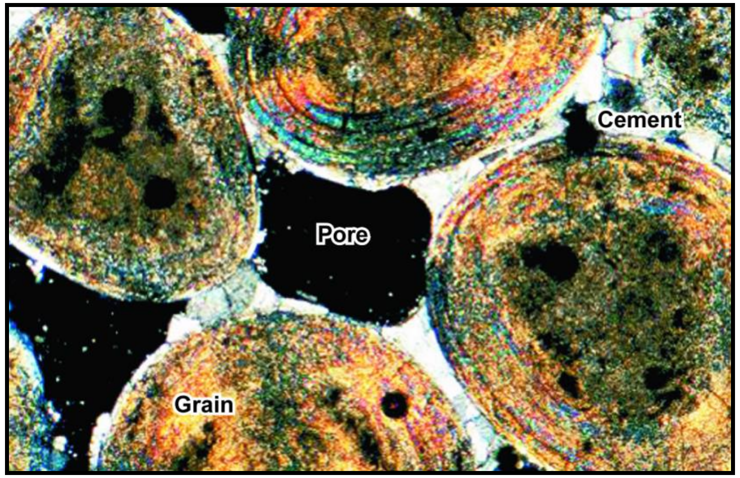


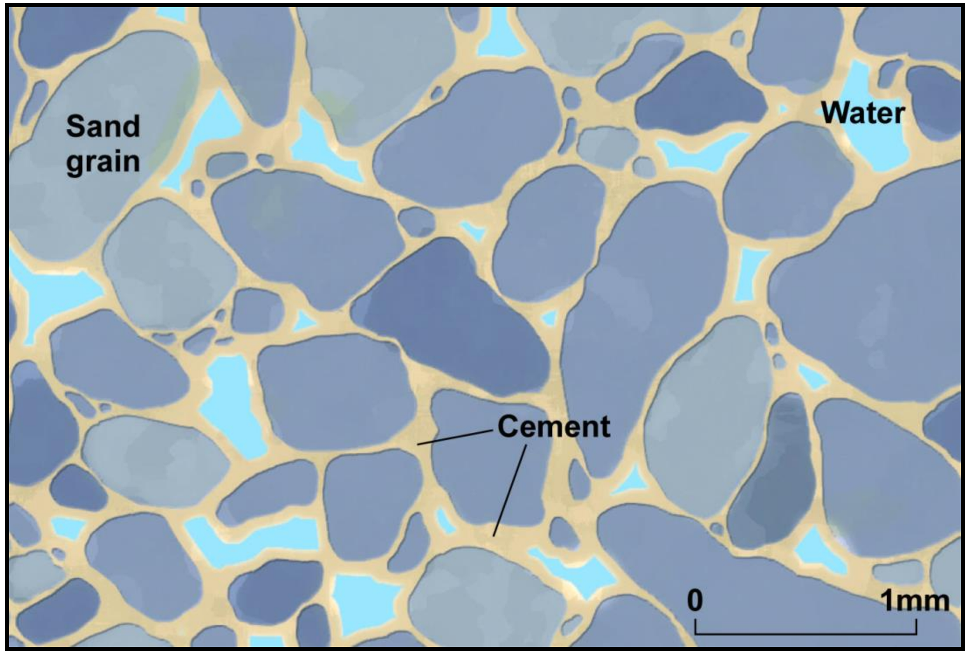
Source Rocks & Hydrocarbon Genesis

- **The shale is buried to 2–4 km depth and warms.**
  - **Heating breaks organics down into waxy kerogen.**
  - **Kerogen-rich source rocks are called oil shales.**
- **Above 90^{o}C, kerogen breaks down into oil.**
- **Oil and gas form within specific temperature ranges:**
  - **Oil and gas: 90^{o}–160^{o}C: *oil window***
  - **Gas only: 160^{o}–250^{o}C**
- **Above 250^{o}C, oil and gas decompose to form graphite.**

Hydrocarbon Systems

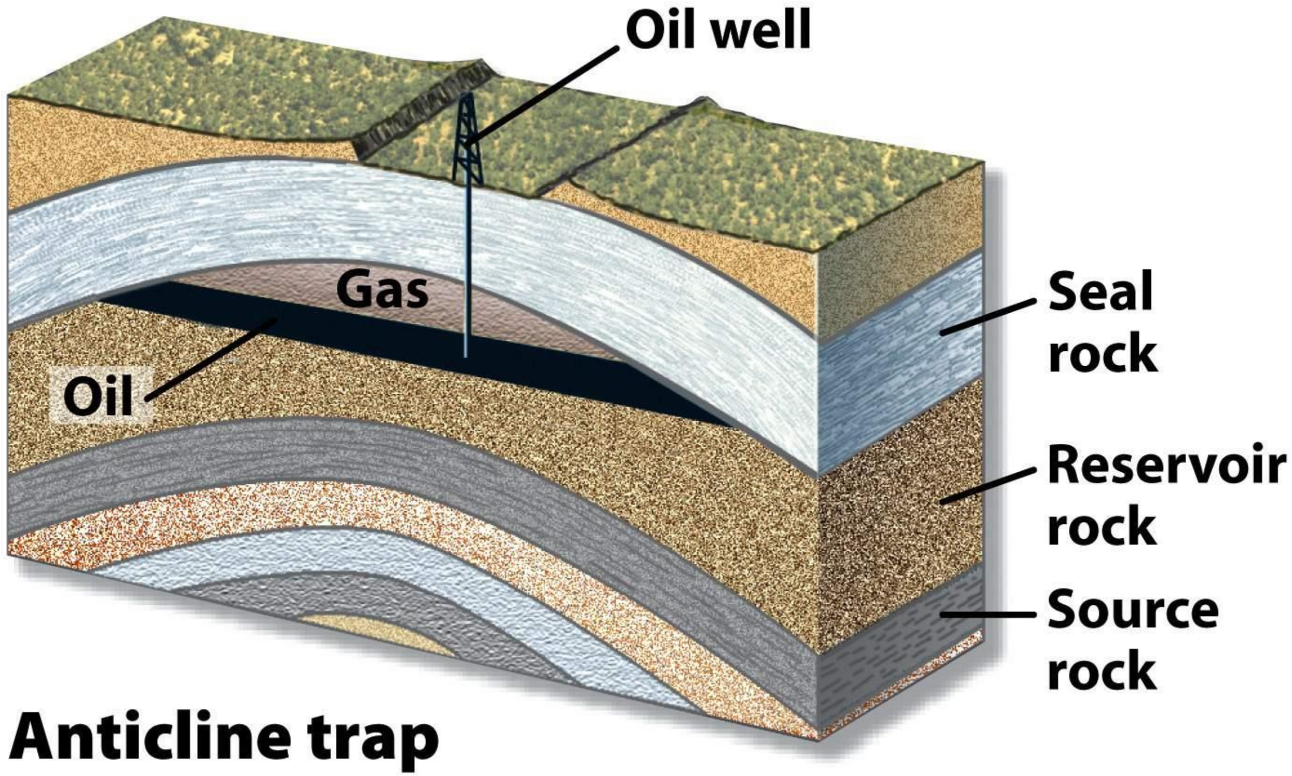
- Reservoir rocks and hydrocarbon migration
  - Reservoir rocks store and transmit oil and gas.
  - Porosity—open space in the rock that stores fluid
  - Permeability—ease of fluid movement through pore space
    - Low—small well yields
    - High—large well yields





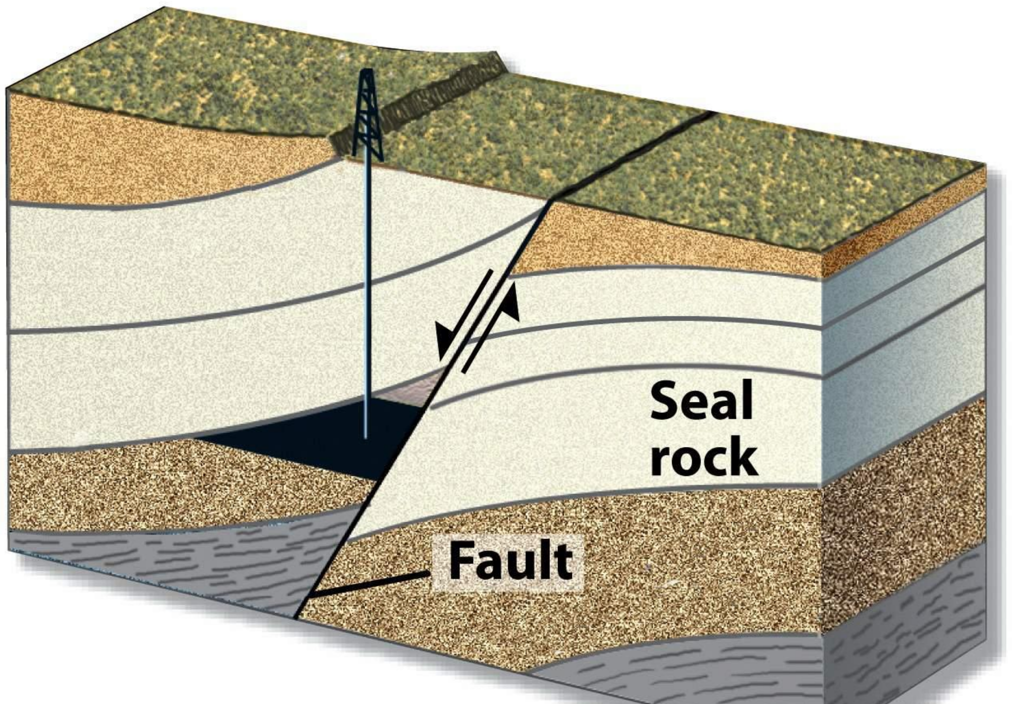
Oil and Gas Traps

- **Traps and seals**
  - **Anticline trap—structural arch trap for oil or gas within a permeable bed such as a sandstone**



Oil and Gas Traps

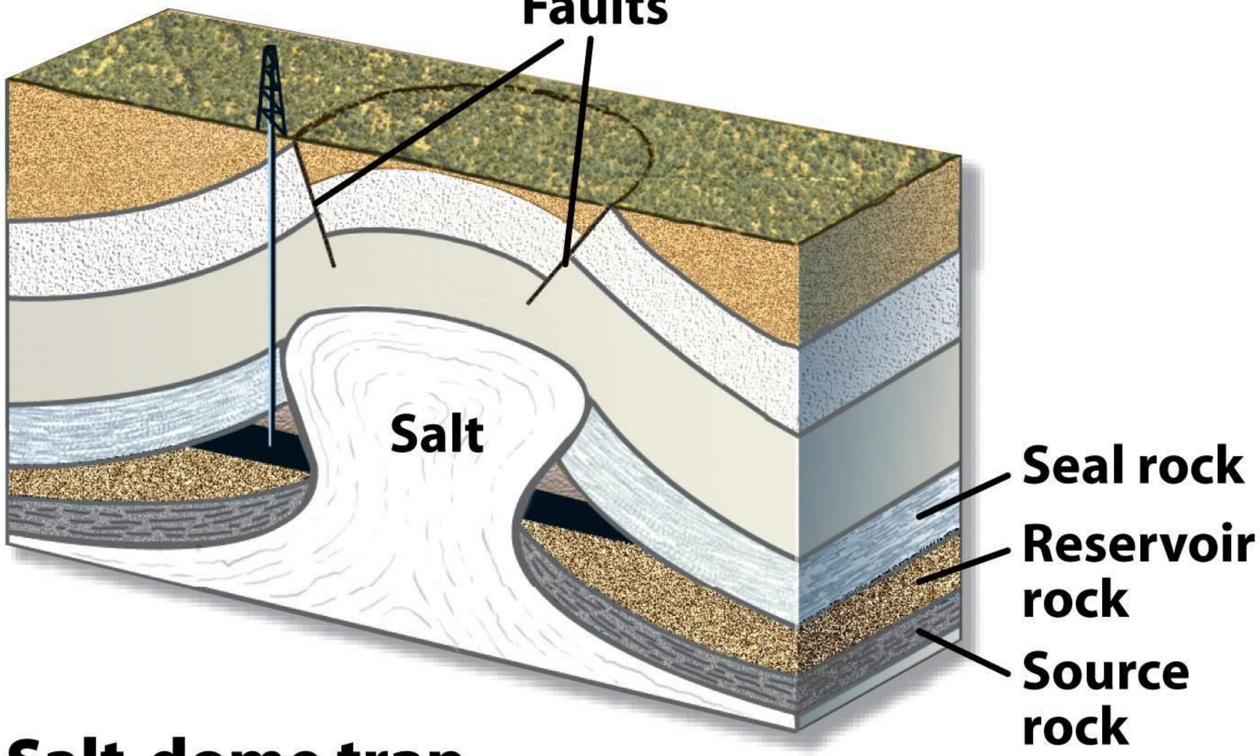
- Traps and seals
  - Fault trap—displacement juxtaposes rocks with varying permeability.



Fault trap

Oil and Gas Traps

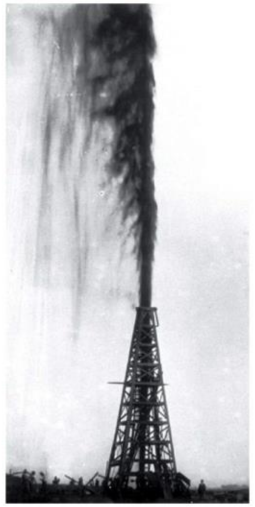
- **Traps and seals**
  - **Salt-dome trap (diaper) — salt buoyancy and plastic flow disrupt nearby rocks, forming traps. Salt-domes produced the first large oil fields that were developed in Texas**

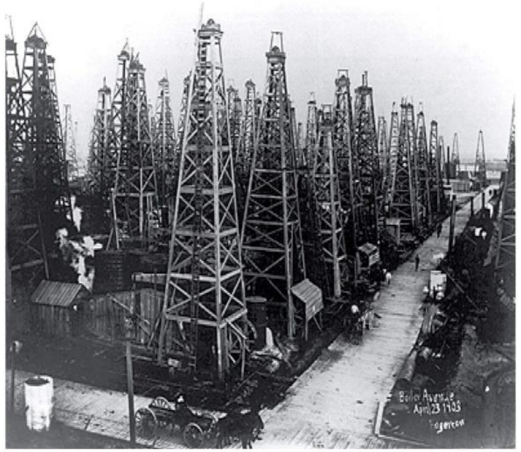


Salt-dome trap

Birth of the Oil Industry

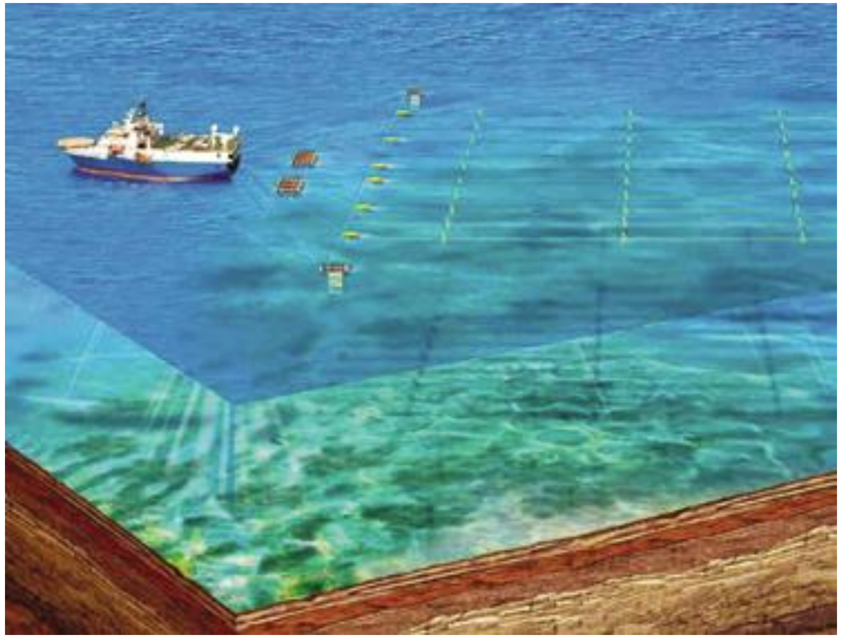
- **Oil from seeps has been used for millennia.**
- **The first commercial oil well in North America was "dug" in August, 1858 at Oil Springs, Ontario by James Wilson. The first "gusher", the Shaw Gusher, was drilled in this area in 1861.**
- **In 1859 an oil well was "drilled" in Titusville, PA. by Edwin Drake. Within a decade, thousands of oil wells had been drilled across North America.**
- **The 1901 Spindletop gusher that ushered in the Texas industry.**

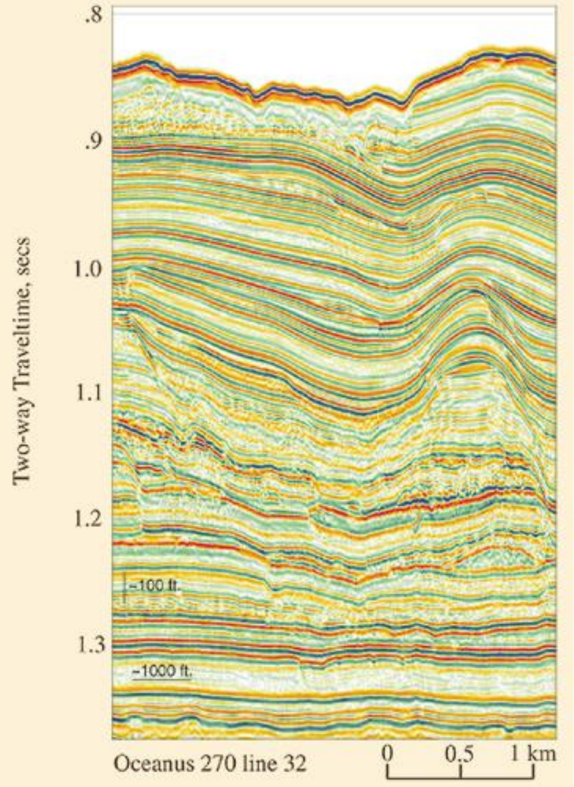




Oil Exploration

- Finding oil reserves requires systematic exploration.
  - Source rocks are always sedimentary.
  - Reservoir and seal rocks are usually sedimentary.
- Seismic reflection profiling is used to construct images of subsurface layers and structures.





Drilling and Refining

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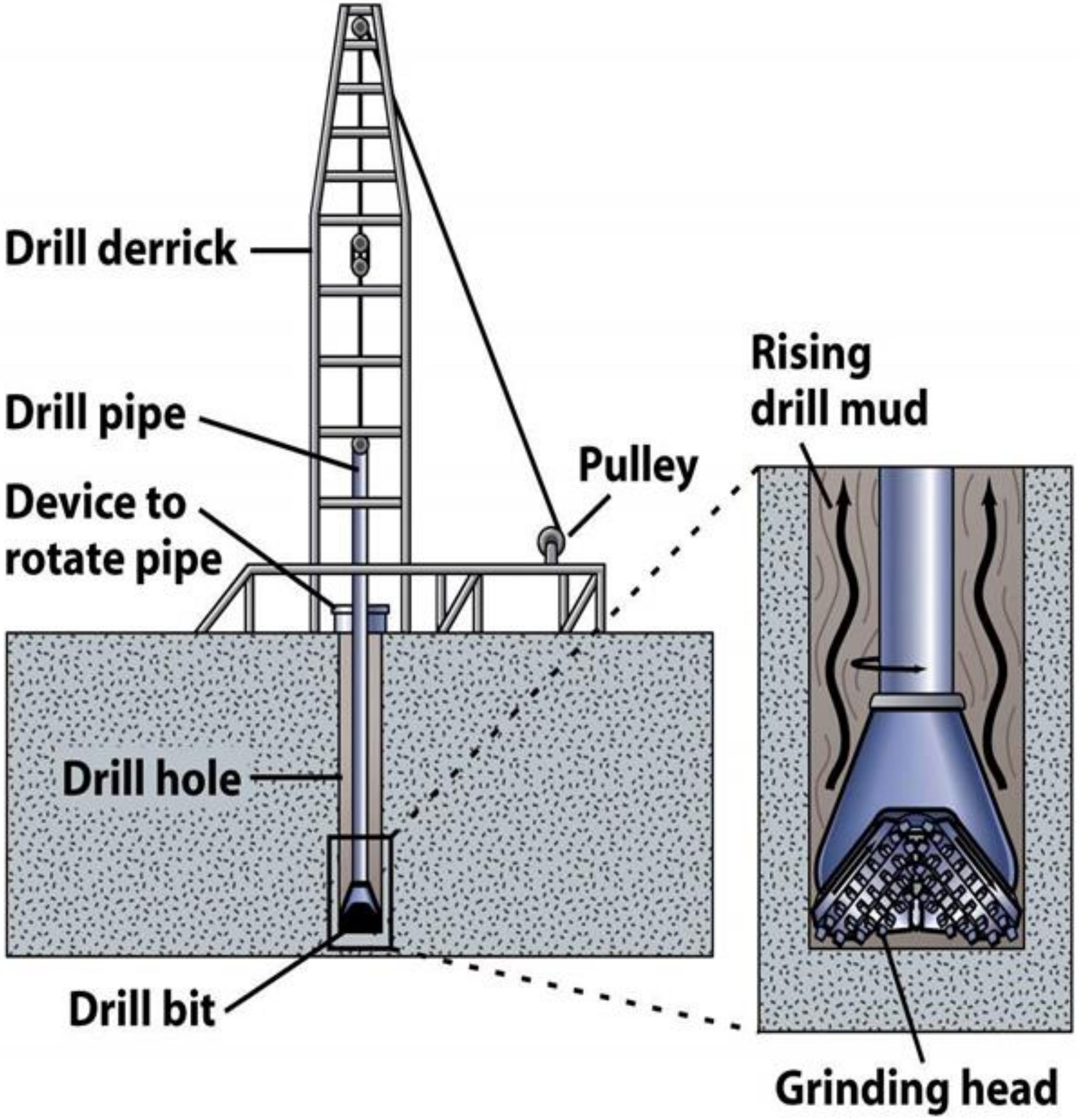
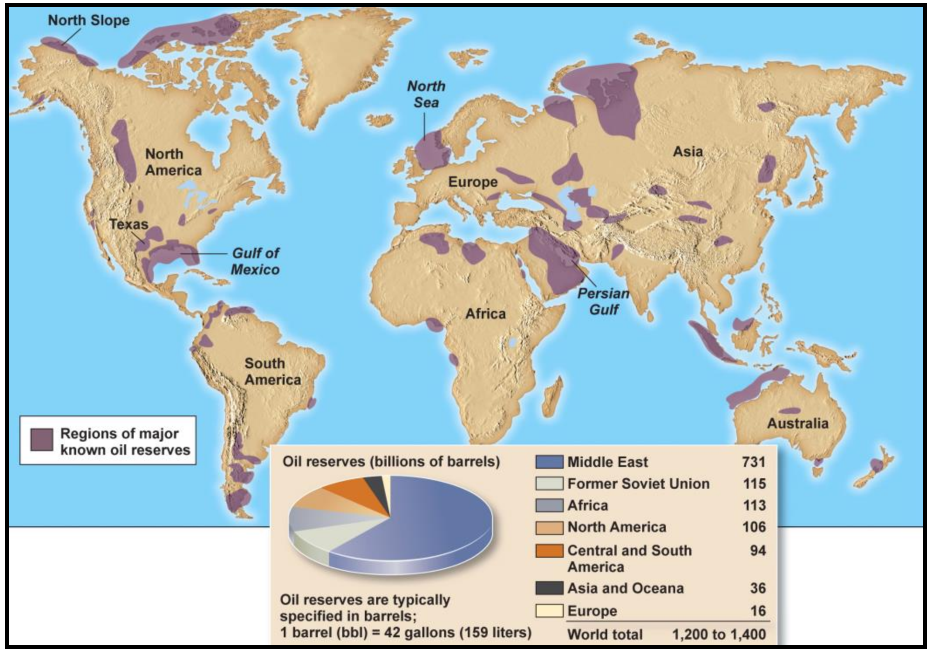


Drilling and Refining

- Crude oil must be refined.
  - Crude oil is distilled into separate mixtures by weight.
  - Lighter molecules rise to the top of distillation columns.
  - Heavier molecules remain at the bottom.
  - Largest molecules left at bottom are made into plastics.

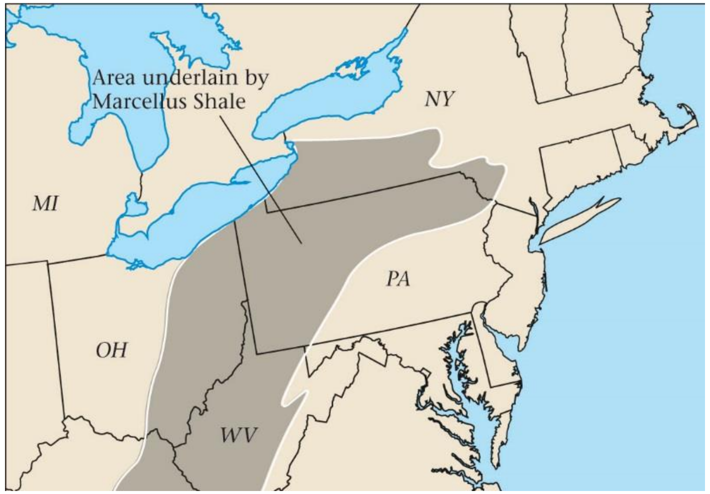
Where Does Oil Occur?

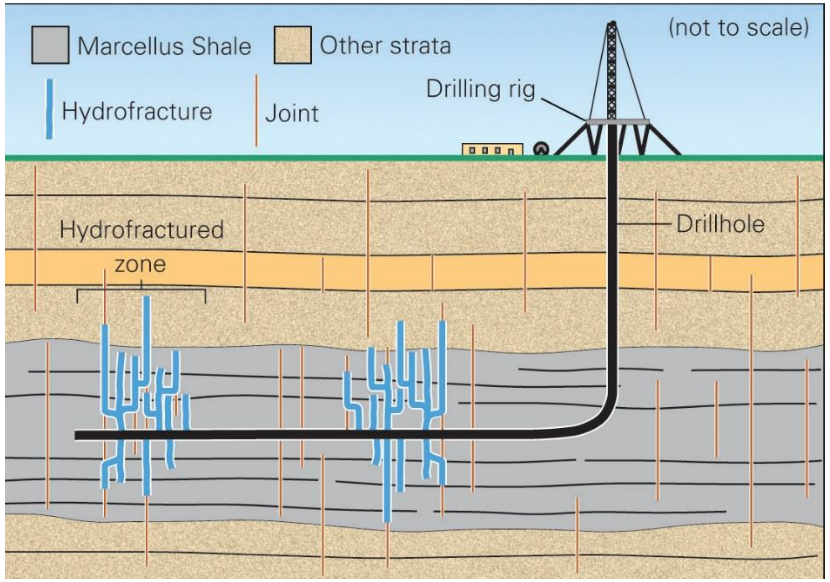
- Oil and gas preservation is geologically rare.
- Countries bordering the Persian Gulf contain the world's largest conventional petroleum reserves.
  - Ideal conditions in Jurassic to Late Cretaceous
  - High biological productivity, preservation of organics
  - Source rock, reservoir rock, and traps well formed
- Many other productive reserves across the globe
- In Canada, the discovery at Leduc, Alberta brought in our oil industry… the oil there is contained in Devonian reefs.



Unconventional Hydrocarbon Reserves

- Natural gas—short-chain hydrocarbons
  - Methane, ethane, propane, butane, and others.
  - Form at temperatures just above the oil window.
  - Natural gas is more abundant than oil; a cleaner fuel.
  - Now being drilled from shale oil, using direction drilling and hydraulic fracturing: "fracking".





Unconventional Hydrocarbon Reserves

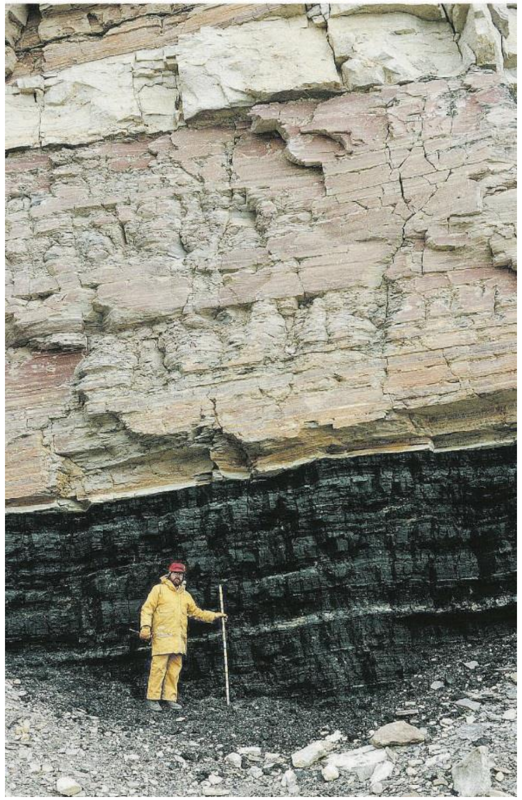
- Tar sands—heavy residual petroleum found in sand.
  - Heavy oil (bitumen) is the residue of a former oil field.
  - Bitumen hydrocarbons are too viscous to be pumped.
  - Tar sands must be mined and processed.
    - Difficult, expensive, inefficient; 2 tons yields 1 barrel of oil.
    - Energy intensive—tar sands heated in furnace to extract oil.
  - Extensive deposits in Alberta, Canada, and in Venezuela.

Unconventional Hydrocarbon Reserves

- Oil shale—a shale containing abundant kerogen
  - A source rock that has not reached the oil window
  - Heating transforms kerogen into liquid hydrocarbon.
  - Shale oil abundant in:
    - Ontario (hist.)
    - Wyoming
    - PA, NY, OH
    - NE BC
    - China
    - Russia
    - Scotland
    - Estonia
    - Quebec (?)

Coal

- Black, brittle, carbon-rich, low-silica sedimentary rock.
- Produced from burial and heating of vegetation.
- Important global energy source; also CO_2 emitter.
- Did not form until land plants evolved ~420 Ma.
- Around 60% of world reserves formed in the Carboniferous Period (354–286 Ma).
- The Carboniferous Period had:
  - Warm climate
  - Broad epicontinental seas.
  - Tropical deltaic wetlands



Coal

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  - Warm
  - Broad
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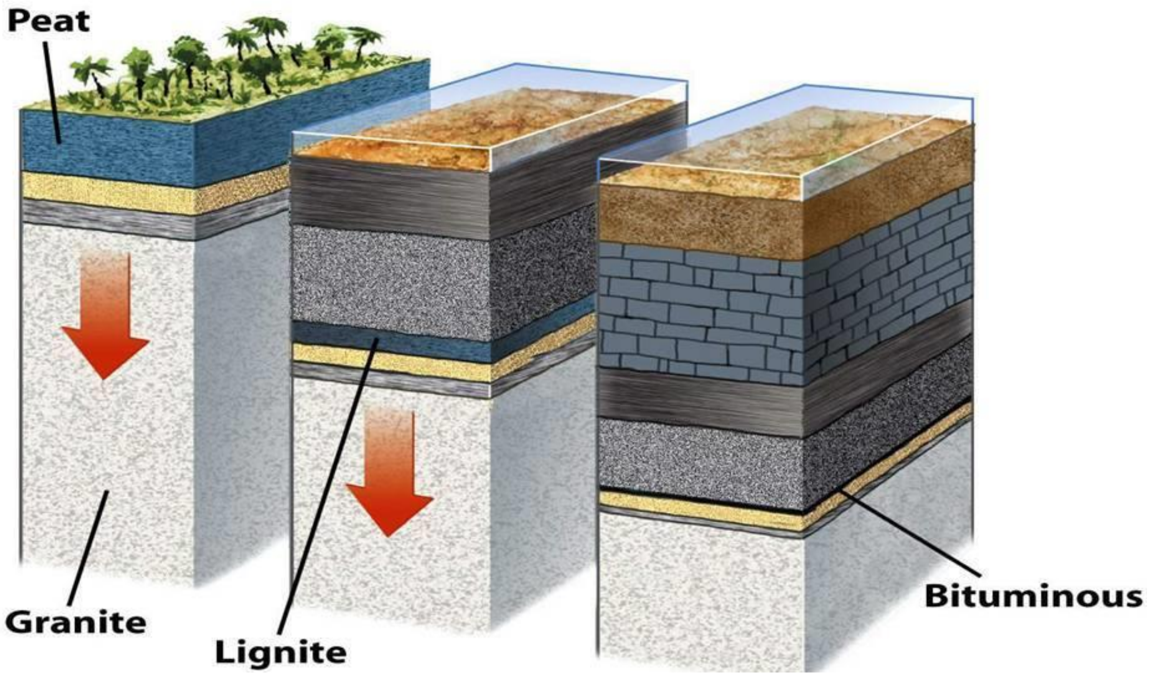
The Formation of Coal

- Compaction and decay turn plant debris into peat.
  - Peat is ~50% carbon.
  - Peat is easily cut, dried, and burned.
- Burial to 4–10 km increased heat and altered the peat.
  - H, N, and S are expelled as gases; C content increases.
  - At > 50% carbon, becomes coal.

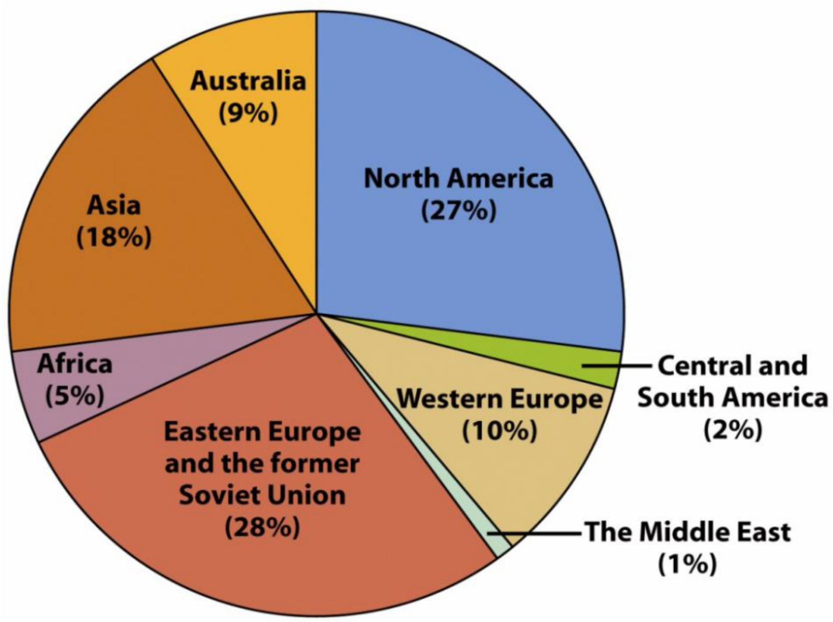


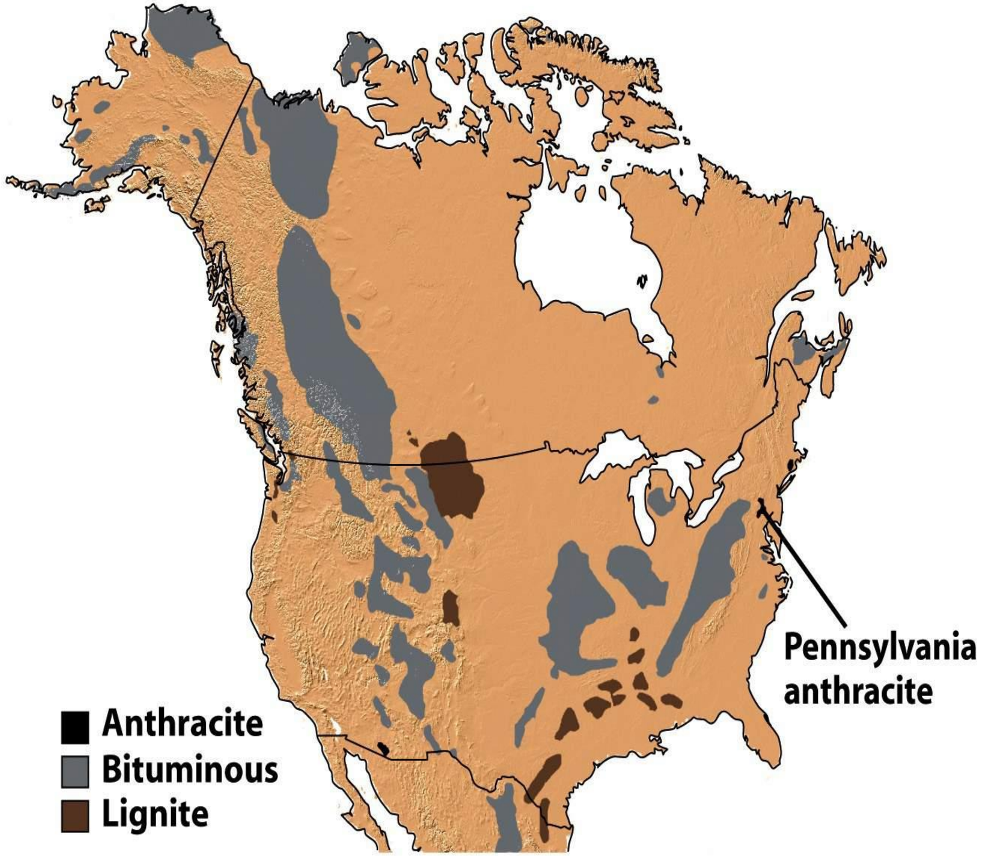
Classification of Coal

- **Classification, or rank, is based on the carbon content.**
- **With increasing burial, *peat* transforms into *lignite*.**
  - **Lignite is soft, dirty, dark-brown, contains ~ 50% carbon.**
- **At 100–200 ºC, lignite turns to *bituminous* coal.**
  - **Bituminous is ~ 70% carbon.**
- **Further heating to 200–300 ºC forms *anthracite* coal.**
  - **Anthracite is ~ 90% carbon.**
  - **Forms along mountain belts.**
  - **8–10km depth.**
  - **Anthracite is “best”**

Finding and Mining Coal

- **Coal deposits are found worldwide.**
  - **The U.S. and Canada have vast bituminous and lignite coal reserves.**
  - **Anthracite is rarer; most has been mined.**



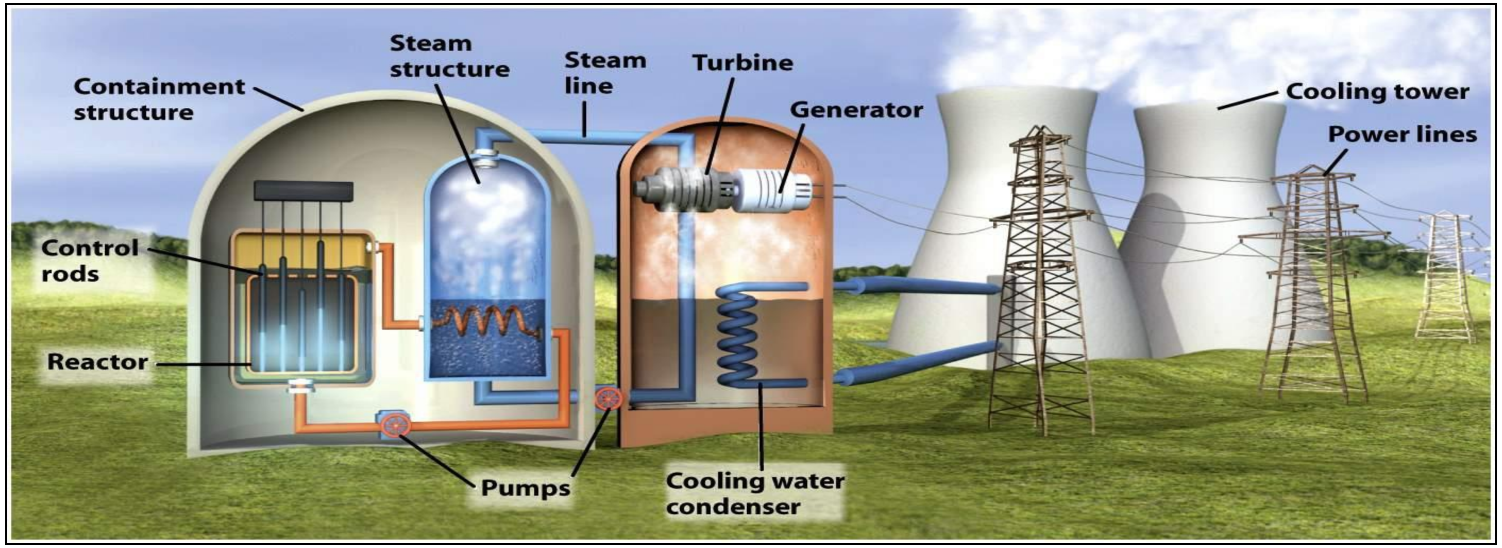


Gas from Coal

- **Coalbed Methane—an energy resource trapped in pores**
  - **Drillers tap deep strata to extract methane—natural gas.**
- **Coal Gasification can transform coal to syngas.**
  - **Coal is extracted and pulverized.**
  - **Steam and oxygen passed through coal at high pressure.**
  - **Flammable coal gas (H_2, CH_4, CO) recovered for use as fuel.**

Nuclear Power

- Energy in a nuclear power plant is derived from fission.
  - Fission splits atoms into smaller pieces, releasing energy.
  - Breaking bonds that hold protons and neutrons together.
- In a nuclear reactor, fission produces enormous amounts of energy.
  - High-pressure steam is created in the reactor.
  - Steam spins turbines in a generator to create electricity.



The Geology of Uranium

- Uranium occurs naturally in many rocks; amount varies.
  - Uranium is leached from plutons and transported by water.
  - Uranium in groundwater may precipitate in fractures and veins as pitchblende (UO_2).
  - Radiation detectors are used to find uranium.
- Not all uranium is the same. U has two major isotopes:
  - ^{238}U: 99.3%—this isotope is not fissionable.
  - ^{235}U: 0.7%—this isotope is fissionable.
    - Used for generating electricity and making bombs
  - ^{235}U must be enriched by factor of 2–3 to be usable as fuel in most reactors. The CANDU reactor – no enrichment.

Challenges of Using Nuclear Power

- Nuclear power plants can be safe if well designed and constructed, placed in safe locations, and operated properly.
- Nuclear fuel must be constantly cooled.
- Rate of fission is regulated with control rods.
  - If not properly controlled, meltdown can occur.
  - Meltdown causes explosion, spreading radiation.
- Fukushima (2011) cast doubt about safe siting and operation of reactors in geologically active areas.

Challenges of Using Nuclear Power

- Mining often leaves radioactive tailings and leachate.
- Fission creates highly radioactive wastes and toxins.
  - Wastes are harmful for thousands of years.
  - Storage/disposal of radioactive wastes is a multifaceted, complex societal issue.
- Chalk River reactor accidents, the first (1952, 1958)
- 1979—Three Mile Island (Pennsylvania) released little radiation but focused U.S. public concern.
- Two nuclear accidents released more radiation, causing human and environmental damage:
  - 1986—Chernobyl weapon and power facility (Ukraine)
  - 2011—Fukushima power plant (Japan)
  - Since Chalk River, there have been 33 serious incidents.

Other Energy Sources

- **Not all energy options require digging, pumping, or processing to produce chemical or nuclear fuel. These alternatives produce little to no CO_2 and are renewable:**
  - **Geothermal energy**
  - **Ground-source heat**
  - **Hydroelectric power**
  - **Wind energy**
  - **Solar power**

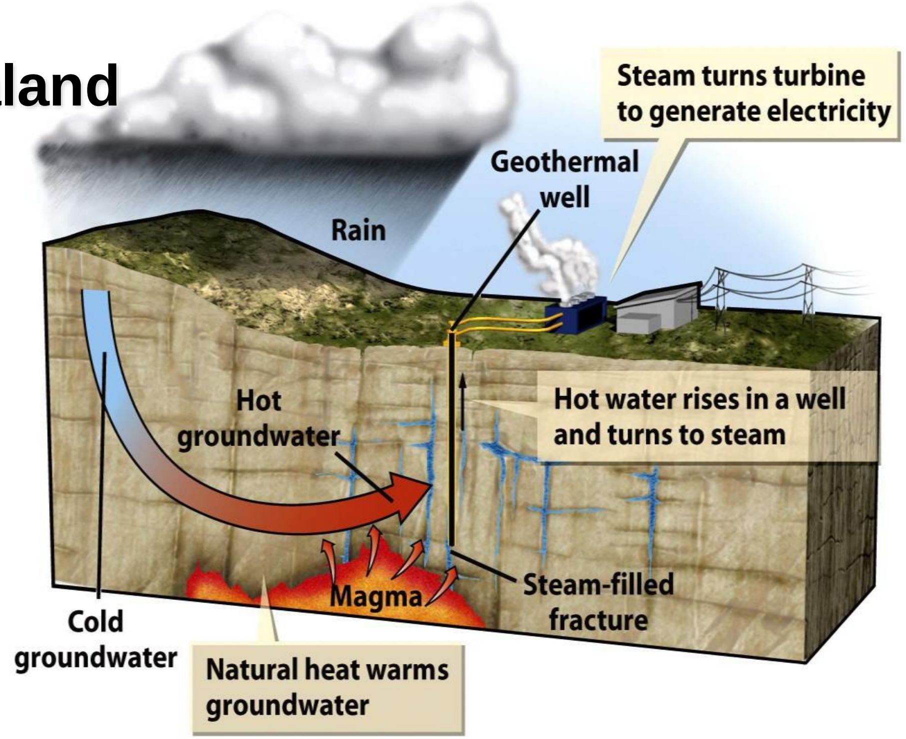
- **Other (not energy sources)**
  - **Chemical batteries**
  - **Hydrogen (the energy vector) fuel cells**
- **Biofuels—processed or refined plant matter**
  - **Semi-renewable; produce CO_2 when burned, but recycles naturally**

Biofuels

- Biofuel—processing plant and animal matter
  - Early humans used biomass (wood, charcoal, dung).
  - Ethanol is the most commonly used biofuel today.
    - Alcohol derived from corn, sugar cane, cellulose, algae, etc.
    - Added to gasoline as a motor vehicle fuel
  - Biodiesel is also an important biofuel.
    - Produced by chemical modification of fats and vegetable oils

Geothermal Energy

- Energy from Earth's internal heat.
  - Geothermal gradient: Earth becomes hotter with depth.
- Hot groundwater pumped to heat buildings, pools, spas.
- Steam from very hot groundwater can be used for electricity generation.
  - California, Iceland, New Zealand



Hydroelectric Power

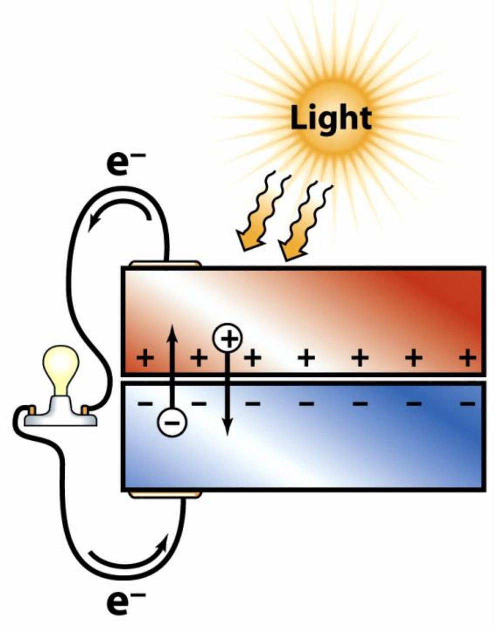
- Running water represents kinetic energy (KE).
- Dams halt the flow of water, converting KE to potential energy (PE) by storing water at higher elevation.
  - Water is released, converting PE back to KE, and flows through turbines to create electricity.
  - Largest hydroelectric plant is Three Gorges Dam, Yangtze River, China.
  - Quebec has about 40GW installed.
- Harnessing tidal power is an emerging technology

Wind Power

- **Wind turbines are enjoying a renaissance.**
  - **Wind turns turbines to produce electricity.**
  - **Wind farms can be on land and offshore in coastal region.**
  - **Towers can be well over 120 m tall, fan blades 70 m long.**
  - **Wind electricity is renewable; does not produce CO_2.**

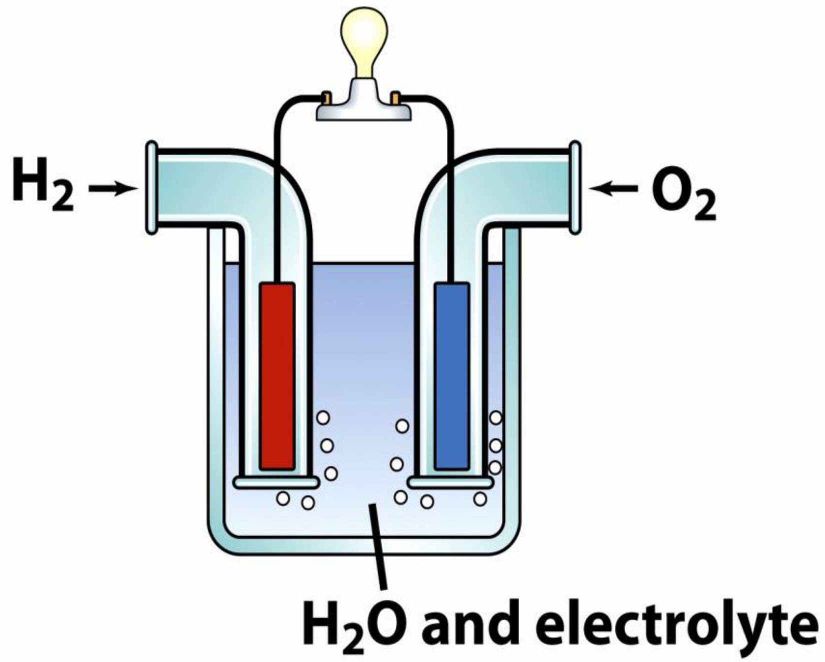
Solar Energy

- The most abundant energy source at Earth's surface
- Can be used to heat water (solar-thermal)
- Photovoltaic panels are used to convert light to electricity.
  - Two wafers of silicon, one doped with B, one with As
  - Light strikes surface; As releases electrons, flow to B
  - Wire connects the two wafers; electric current is captured



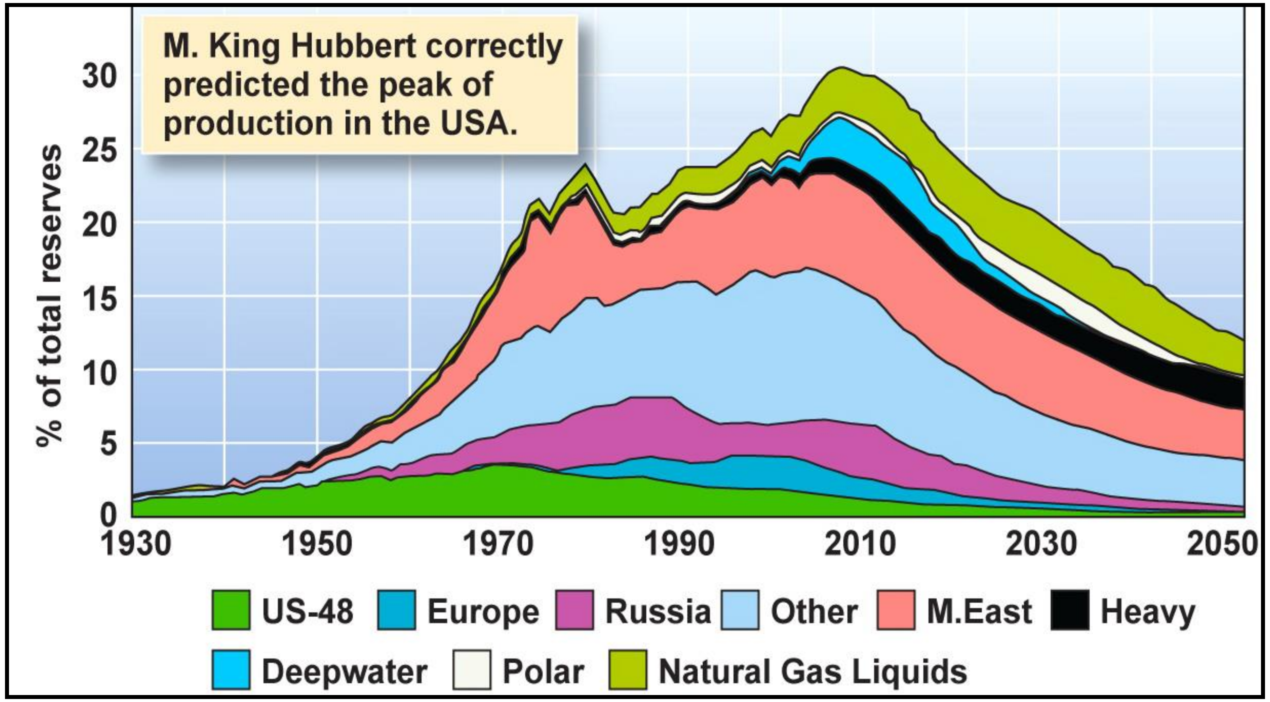
Fuel Cells

- Produce electricity via chemical reactions – *not a "source" of energy* – a way of converting energy!
- Hydrogen (H_2) and oxygen are reacted to yield electricity, heat, and water in "fuel cells."
- Fuel cells are efficient and clean.
- But we need H_2 and there are almost no natural sources
- Technological challenges:
  - H_2 is energy-intensive to produce.
  - H_2 is dangerous to store.
    - Explosive gas!



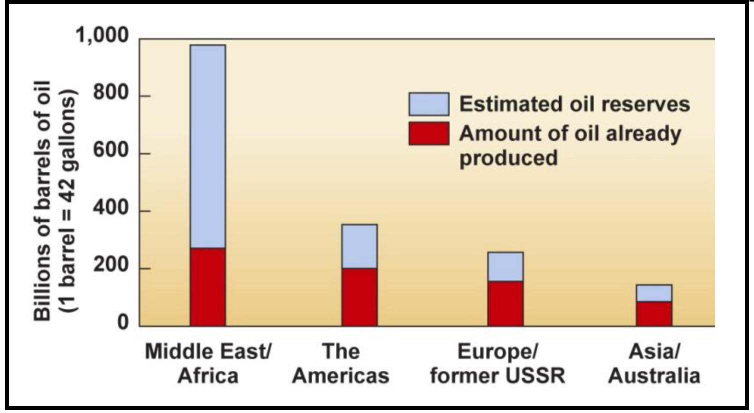
Energy Choices, Energy Problems

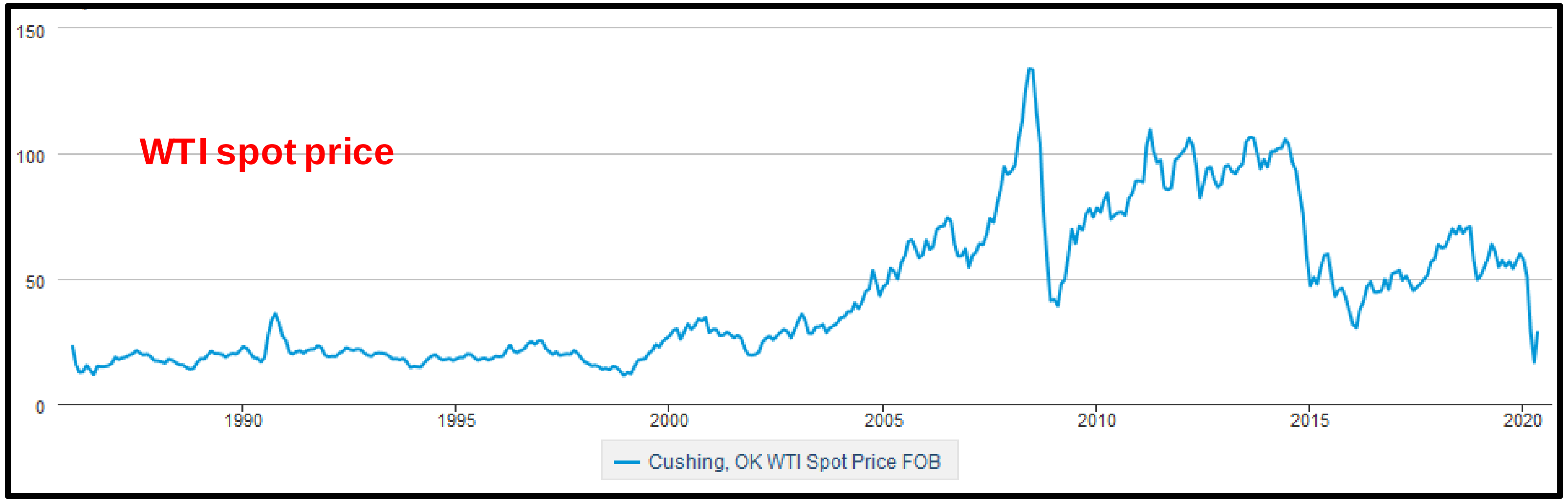
- Global energy use has increased dramatically.
- Use reflects industrialization and population growth.
- Peak Oil -- the dominant energy source—is dwindling. We are near the peak of conventional global oil production; fracking has extended the time to peak.



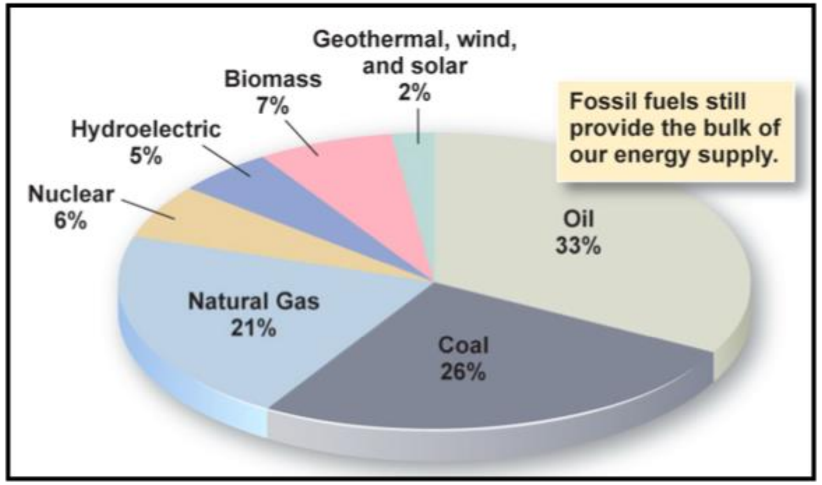
Energy Choices, Energy Problems

- Oil—the dominant energy source—is dwindling.
- Many countries import oil to meet demands.
- Shortages and rising prices create economic problems and political conflicts.





Energy Resources – current usage



Non-renewables

- Oil reserves: 30 – 200 years
- Coal reserves: > 100 years
- CH_4: 100-1000 years
- U/Th reserves: > 10k yr
- Geothermal (fossil?)

Convert to renewables

- Geothermal (fossil) > virtually forever
- Hydroelectric power is, perhaps, already 20% exploited. Wind…
- Solar … perhaps ~ 100x current energy is continually served by the Sun

Environmental Issues

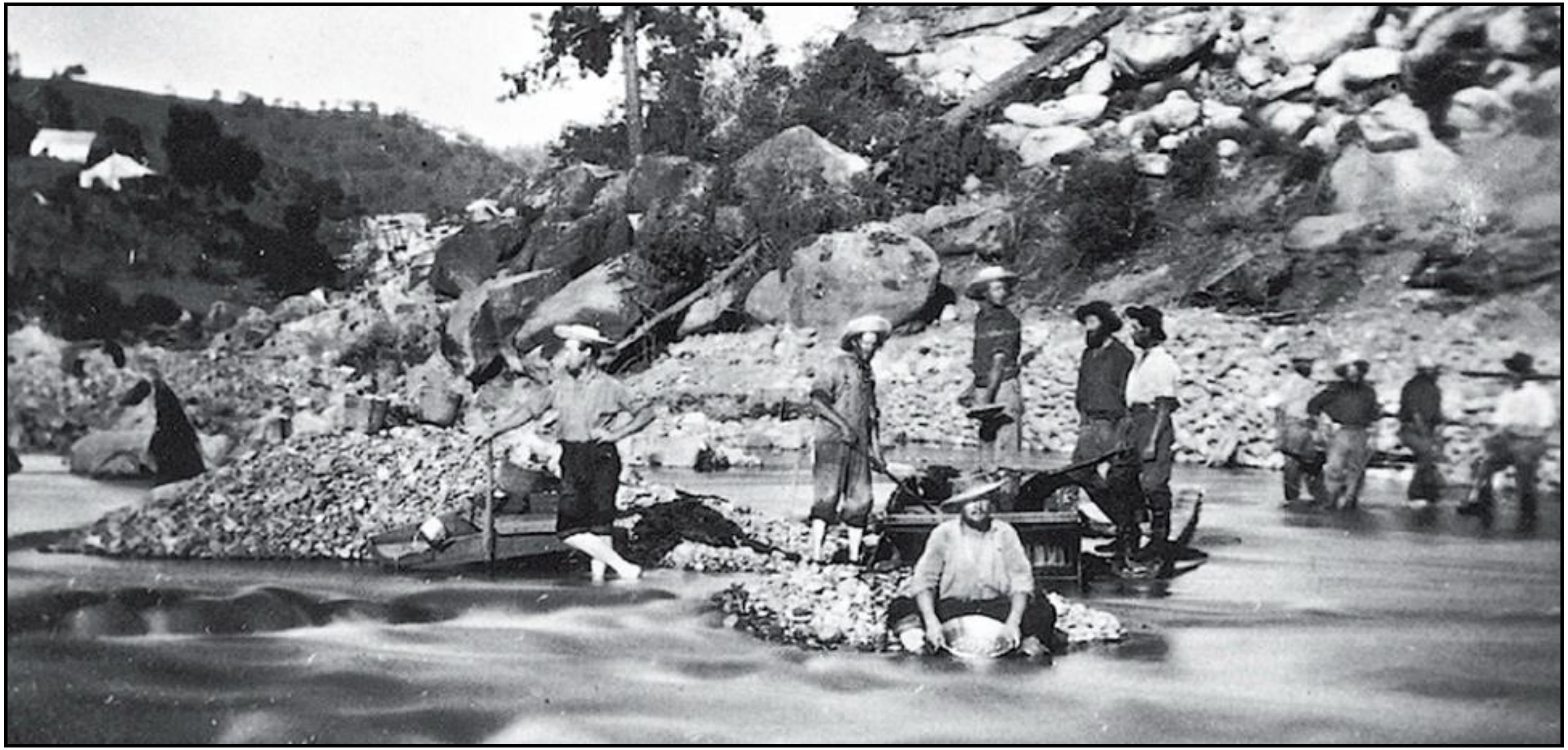
- **Fossil fuel production and use damage the environment.**
  - **Oil spills—*Deepwater Horizon* spill, Gulf of Mexico**
  - **Coal—strip mining, mountaintop removal, acid drainage**
  - **Shale gas—groundwater contamination from “fracking”**
  - **Nuclear power—radiation releases and destruction of Fukushima and Chernobyl stations.**

Environmental Issues

- Using fossil fuels causes air pollution, affects climate.
  - Unburned hydrocarbons add to photochemical smog.
  - Sulfur dioxide (SO_2) contributes acid rain.
  - Burning coal lofts toxic metals and soot into the air.
  - CO_2 stimulates global warming and climate change.

Introducing Mineral Resources

- **Quest for mineral resources has a rich human history.**
  - **Native American copper trade, Spanish conquistadors**
  - **California and Klondike gold rushes**

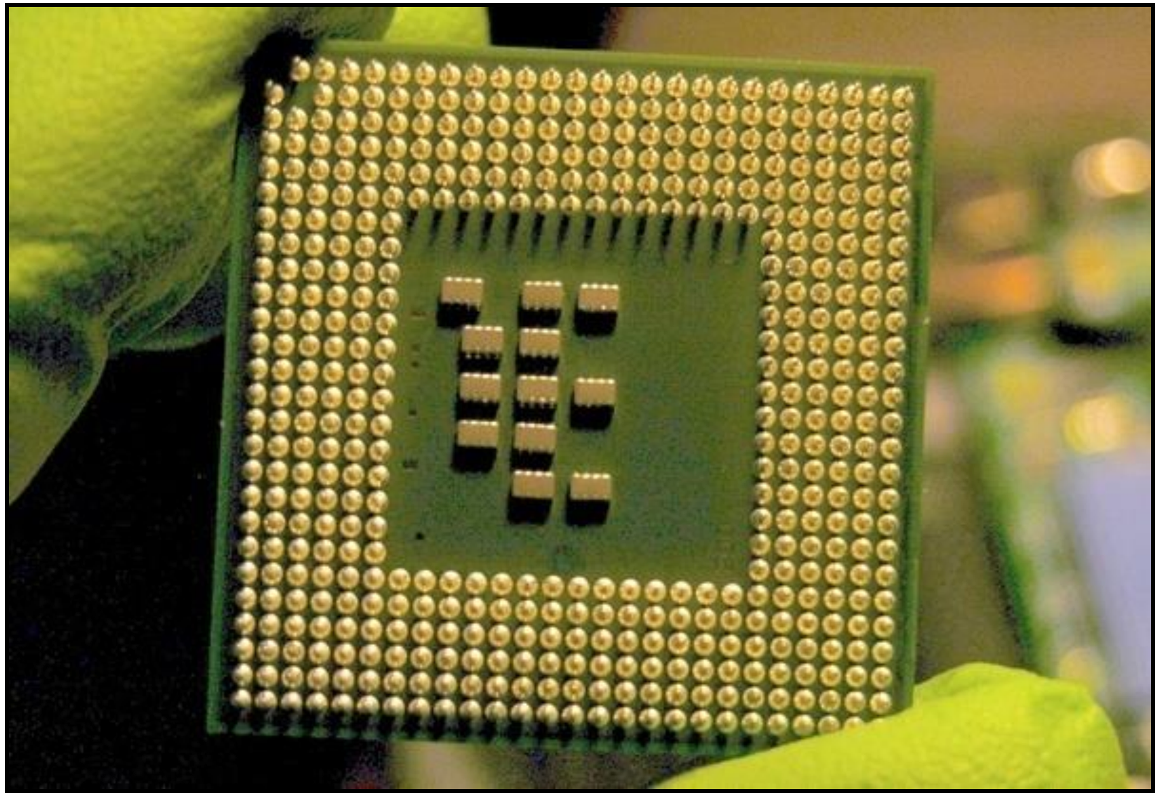


Introducing Mineral Resources

- Two major categories:
  - Metallic:
    - Gold
    - Silver
    - Copper
    - Lead
    - Zinc
    - Iron
    - Aluminum
  - Nonmetallic:
    - Sand and gravel
    - Gypsum
    - Phosphate
    - Building stone

What Is a Metal?

- Opaque, shiny, smooth, conductive solids
- Metal properties derive from metallic chemical bonds.
  - Delocalized electrons move from atom to atom easily.
  - Electron fluidity renders metals electrically conductive.



Metal and Its Discovery

- Metal properties are due to bond type and structure.
  - Metals may be extremely hard (titanium) or soft (copper, gold).
    - Ductile—able to be drawn into thin wires
    - Malleable—able to be hammered into thin sheets
- Native metals occur naturally in a pure form:
  - Gold
  - Silver
  - Copper
  - Iron
  - Electrum

Gold bracelets on display in a Kuwaiti marketplace.

- People have utilized native metals for thousands of years; they have been essential to the evolution of our modern industrial society.

What Is an Ore?

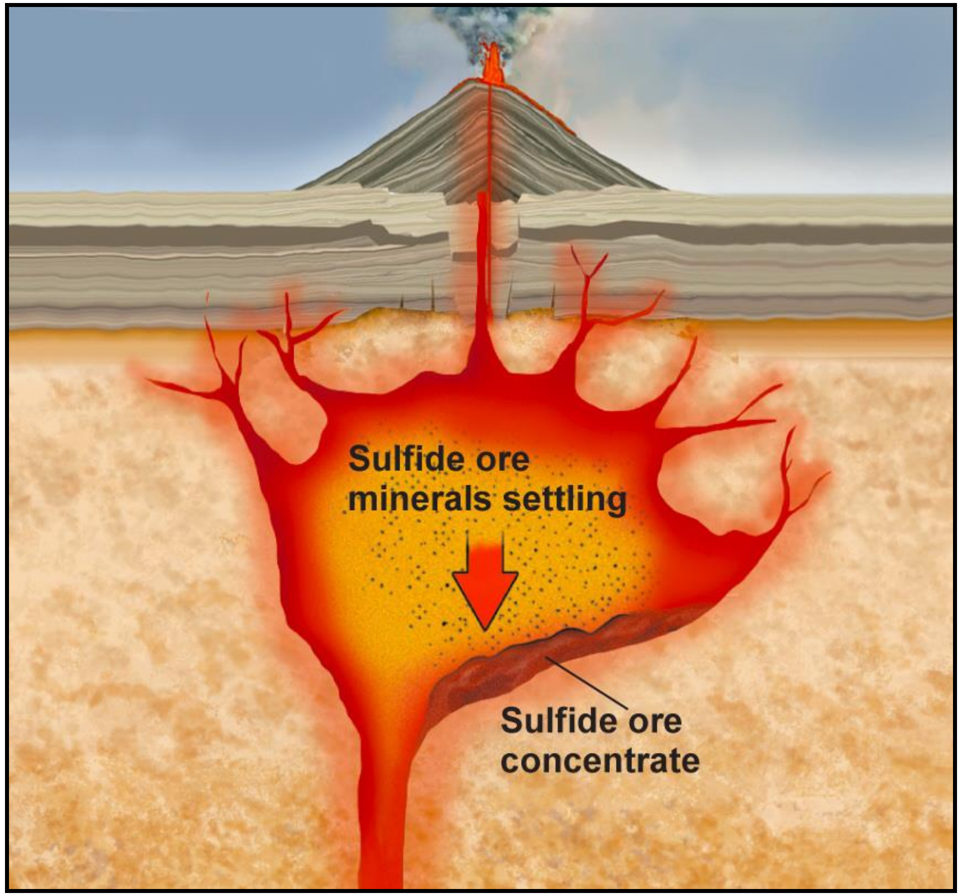
- Rock with metal-rich minerals
  - Concentrated enough to be economic to mine.
  - Concentration determines ore's grade.
  - Metal must be readily extractable from the mineral.
  - There are many different ore minerals for many metals.
  - Many are sulfides or oxides.

How Do Ore Deposits Form?

- Ores form via geological processes.
  - Magmatic activity
  - Hydrothermal alteration
  - Secondary enrichment
  - Groundwater transport (MVT in limestones)
  - Sedimentary deposits
  - Residual mineral deposits
  - Placer deposits

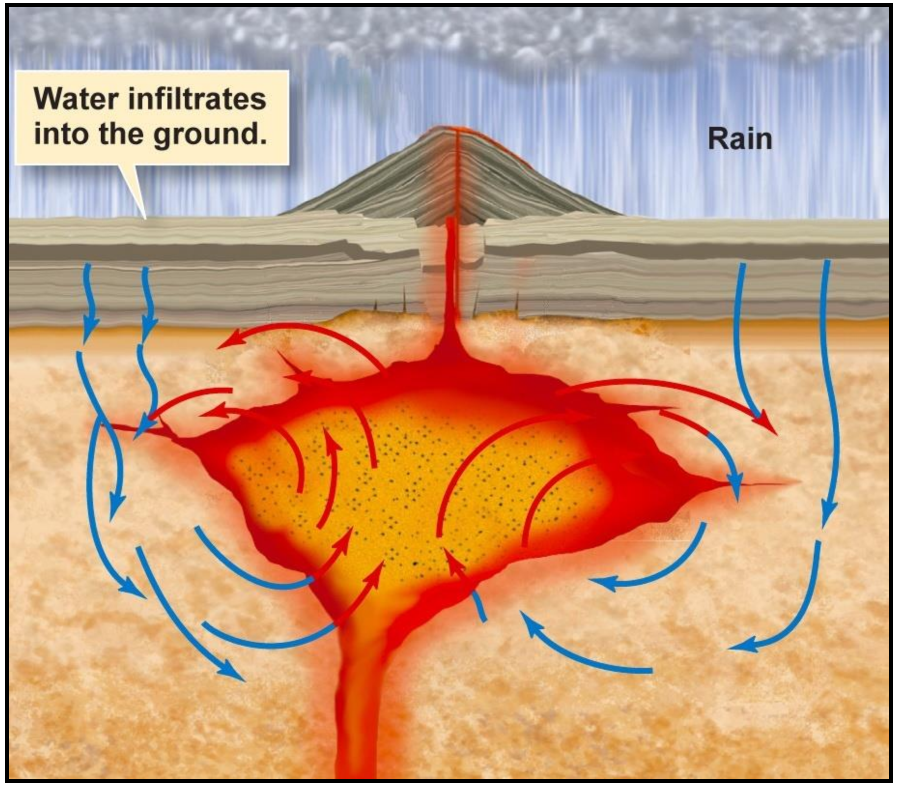
How Do Ore Deposits Form?

- Magmatic deposits—from a cooling plutonic intrusion.
  - Sulfide minerals crystallize early and sink in magma.
  - Form *massive-sulfide deposits* at the bottom of chamber.
  - Sulfides include:
    - Pyrite
    - Chalcopyrite
    - Galena



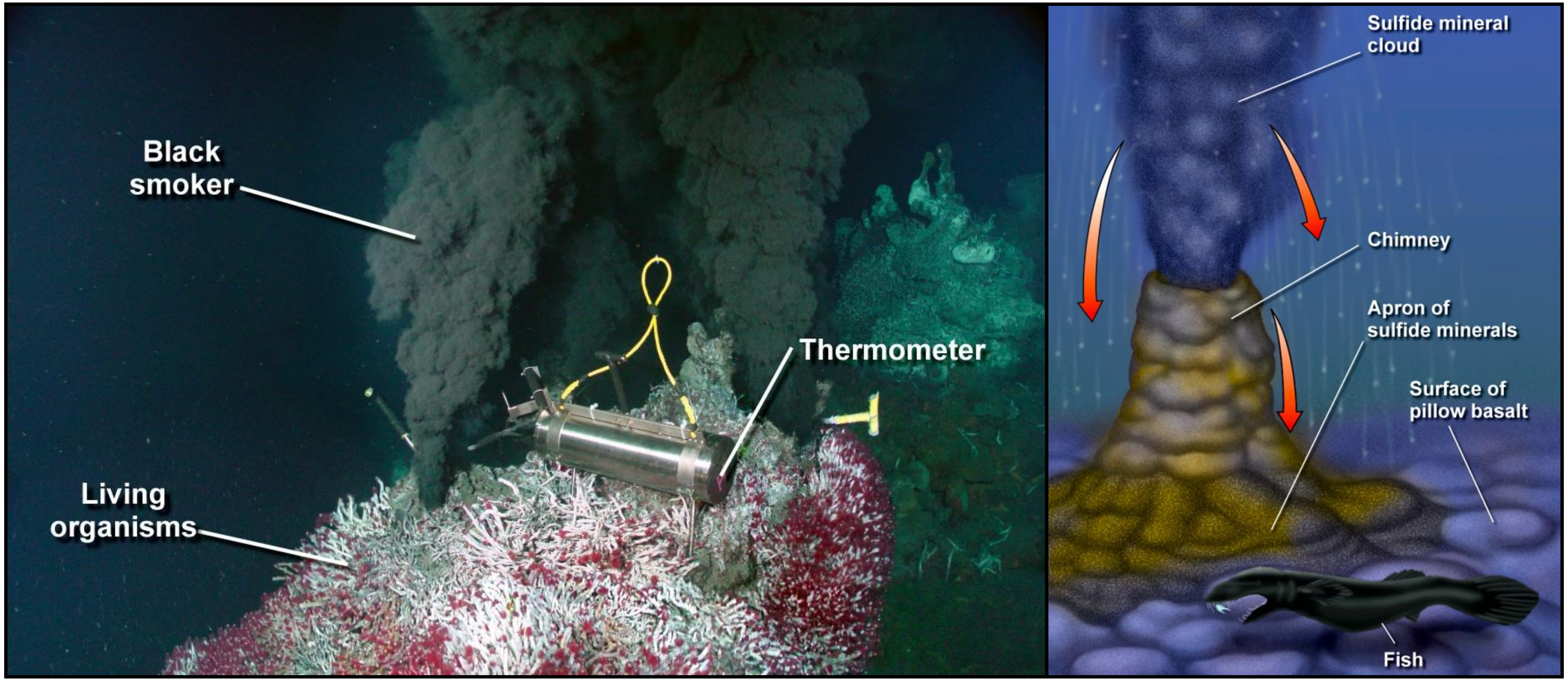
How Do Ore Deposits Form?

- Hydrothermal deposits—hot, chemically active water
  - Hot fluid leaches metal ions out of rock near plutons.
  - Metasomatic processes
  - Minerals precipitate in lower P and T locations.
  - Disseminated through intrusion or in veins.



How Do Ore Deposits Form?

- Hydrothermal deposits—found near mid-ocean ridges.
  - Black smokers—occur along all mid-ocean ridges.
    - Seawater in cracked, hot crust is heated, leaching metals.
    - Hot water hits the cold ocean and metals crystallize out.

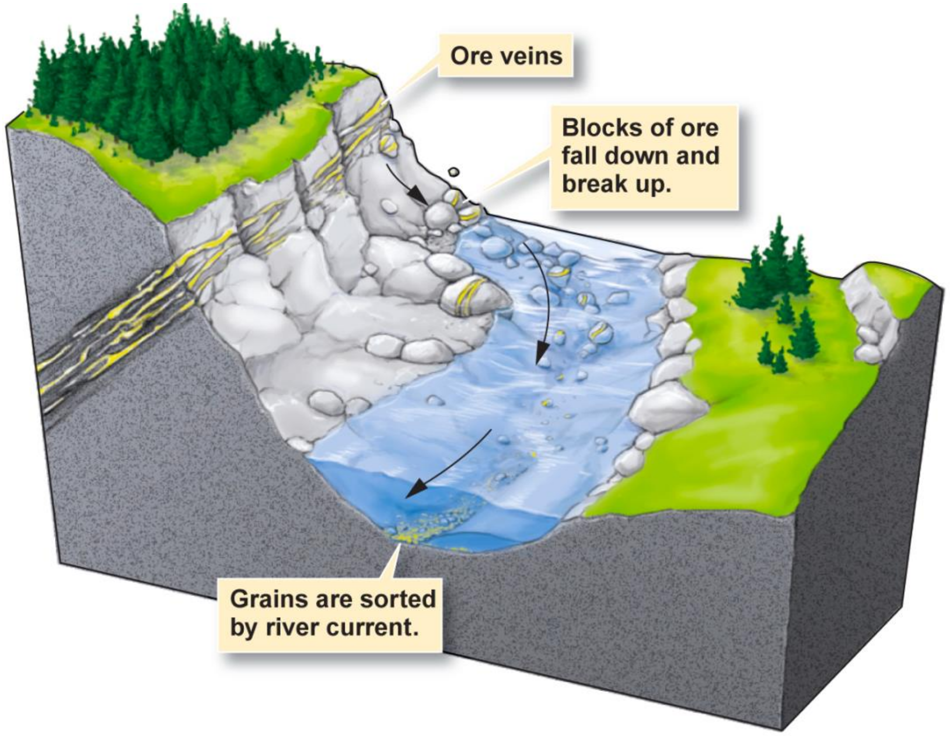


How Do Ore Deposits Form?

- Secondary-enrichment deposits—adds O_2, OH, and CO_2.
  - Groundwater leaches and oxidizes primary sulfide ores.
  - The secondary deposit often has beautiful minerals.
    - Malachite—copper ore
    - Azurite—copper ore

How Do Ore Deposits Form?

- Placer deposits—hydraulic sorting by flowing water
  - In high-velocity water:
    - Low-density minerals are suspended and washed away.
    - High-density grains are concentrated by settling out.
  - Important for gold, tin, and iron
  - Best preserved in fossil stream sediments
  - Ore source can be traced upstream.



Ore Exploration and Production

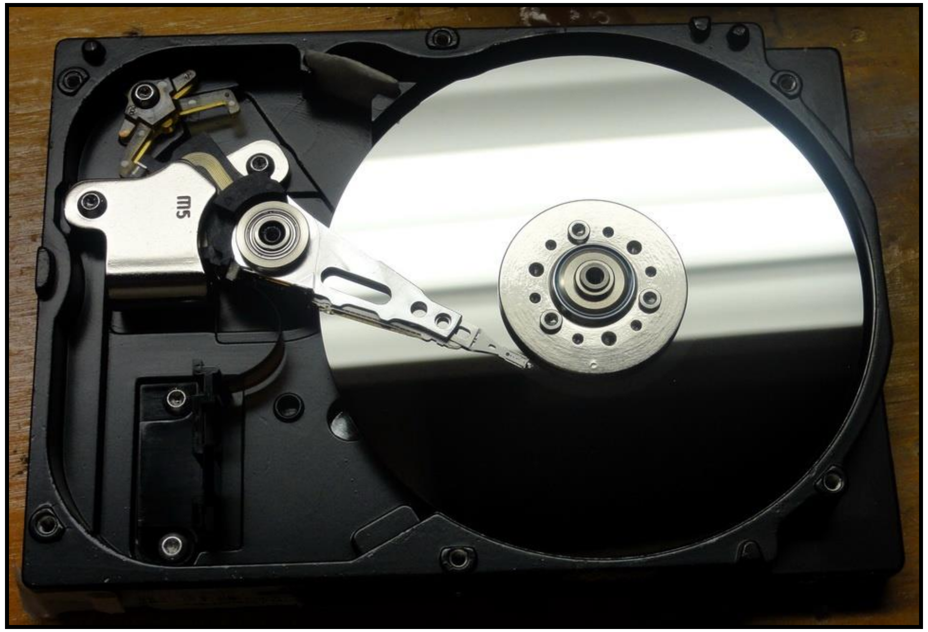
- Shallow ore bodies—open-pit mining
  - Less expensive and dangerous than tunnel mines
  - Usually require ore within 100 m of the land surface
- Open-pit mining creates large excavations.
  - Rock is broken by explosives and removed for processing.
    - Ore metal is concentrated by treatment or smelting.
    - Waste rock is stored in giant tailings piles.

Nonmetallic Mineral Resources

- Society uses many materials that don't contain metals.
- Nonmetallic resources are called <u>industrial minerals</u>.
  - Dimension stone
  - Crushed stone/concrete
  - Gypsum for wallboard
  - Phosphate fertilizer
  - Sand for glass and as aggregate
  - Salt
  - Many other materials

Nonmetallic Mineral Resources

- **Many nonmetallic minerals are common in homes.**
  - **Calcite—base material of cement and concrete**
  - **Clay—bricks, pottery, porcelain, and other ceramics**
  - **Gypsum—wallboard and plaster**
  - **Quartz—used to make window glass**
  - **Rare earth elements (REEs)—high-tech applications**



How Long Will Resources Last?

- World demand for mineral resources is enormous.
  - Industrialized countries consume vast quantities.
  - The U.S. uses 4 billion tons of geologic materials/year.
    - It requires moving 18 billion tons of material.
    - This is ~ 95x the annual sediment moved by the Mississippi.

- Mineral resources are *nonrenewable*, like coal and oil.
  - They form as the result of geologic processes.
  - These processes are too slow to generate new deposits.
  - Thus, once mined, mineral resources are gone forever.

How Long Will Resources Last?

- We can estimate the expected lifetime of resources.
  - Consumption rates vs. reserve amounts
- Some critical mineral resources are running out.
- New technologies may extend these lifetimes.

TABLE 12.1 Yearly per Capita Usage of Geologic Materials in the United States)

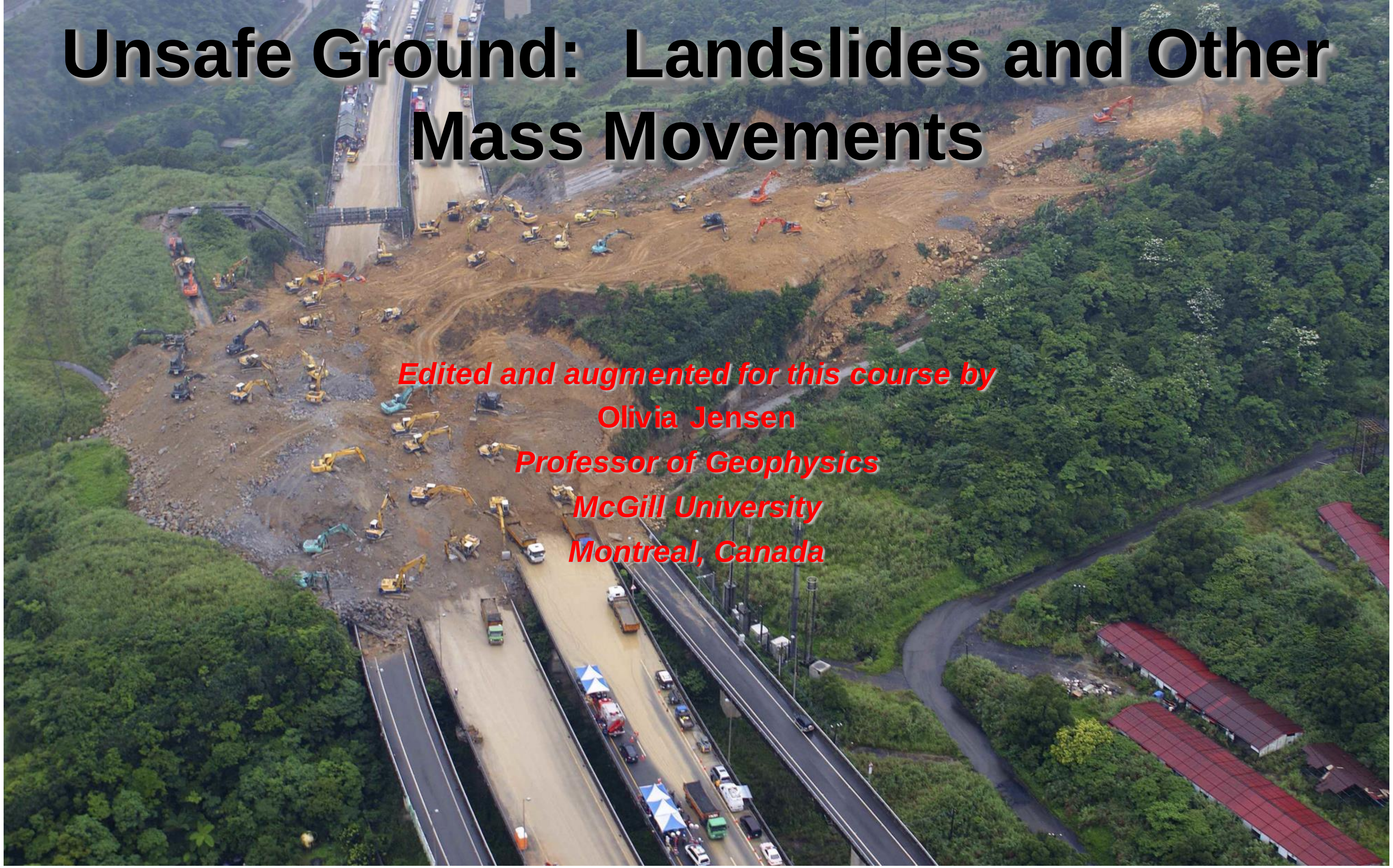
4,100 kg	Stone
3,860 kg	Sand and gravel
3,050 kg	Petroleum
2,650 kg	Coal
1,900 kg	Natural gas
550 kg	Iron and steel
360 kg	Cement
220 kg	Clay
200 kg	Salt
140 kg	Phosphate
25 kg	Aluminum
10 kg	Copper
6 kg	Lead
5 kg	Zinc

1 kg = 2.205 pounds.

TABLE 12.2 Expected Lifetimes of Currently Known Ore Resources (in years)

Metal	World Resources	U.S. Resources
Iron	120	40
Aluminum	330	2
Copper	65	40
Lead	20	40
Zinc	30	25
Gold	30	20
Platinum	45	1
Nickel	75	less than 1
Cobalt	50	less than 1
Manganese	70	0
Chromium	75	0

Unsafe Ground: Landslides and Other Mass Movements



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Introduction

- Earth’s surface is not terra firma; it is mostly unstable.
- Mass movement (or mass wasting) is:
  - Downslope motion of rock, soil, sediment, snow, and ice
  - Driven by gravity operating on any sloping surface
  - Characterized by a wide range of rates (fast to slow)

Mass Movements

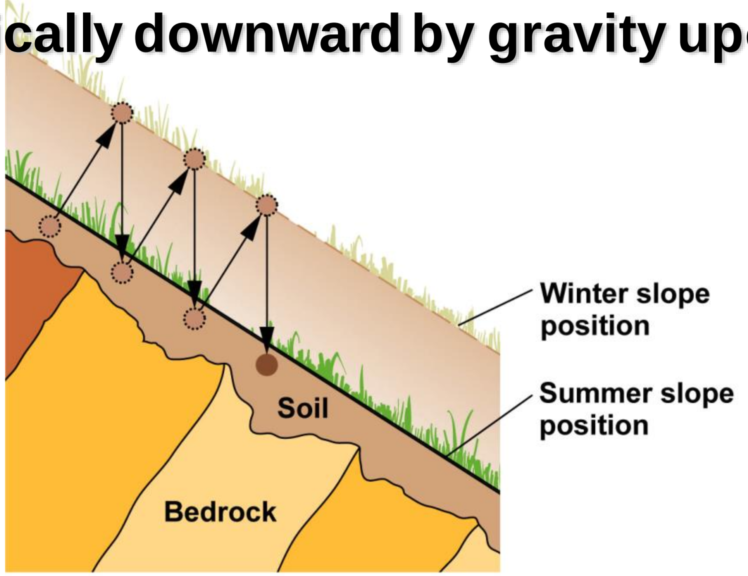
- Mass movements are a costly type of natural hazard.
  - A crucial component of the rock cycle
  - May often cause damage to living things and buildings.
- These hazards can produce catastrophic losses.
  - May 31, 1970: 18,000 people were buried in Yungay, Peru.

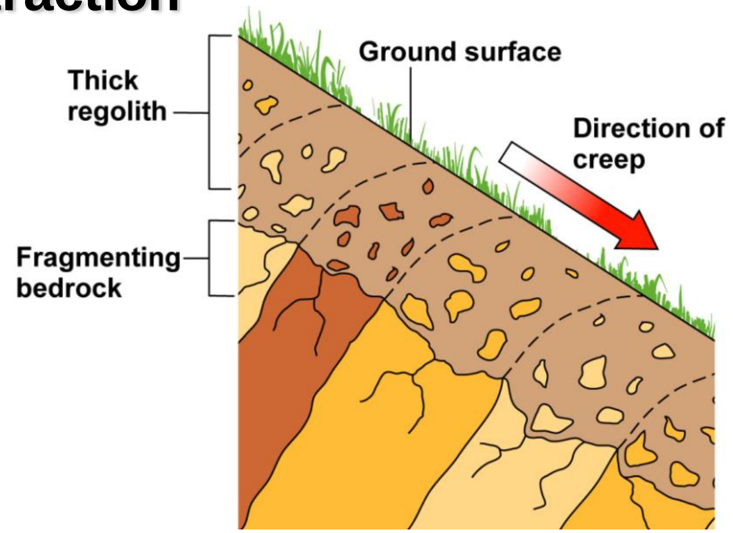
Mass Movements

- Mass movements are important to the rock cycle.
  - The initial step in sediment transportation
  - A significant agent of landscape change
- *All slopes are unstable*; they change continuously.
- Mass movement is often caused by human activity.

Types of Mass Movement

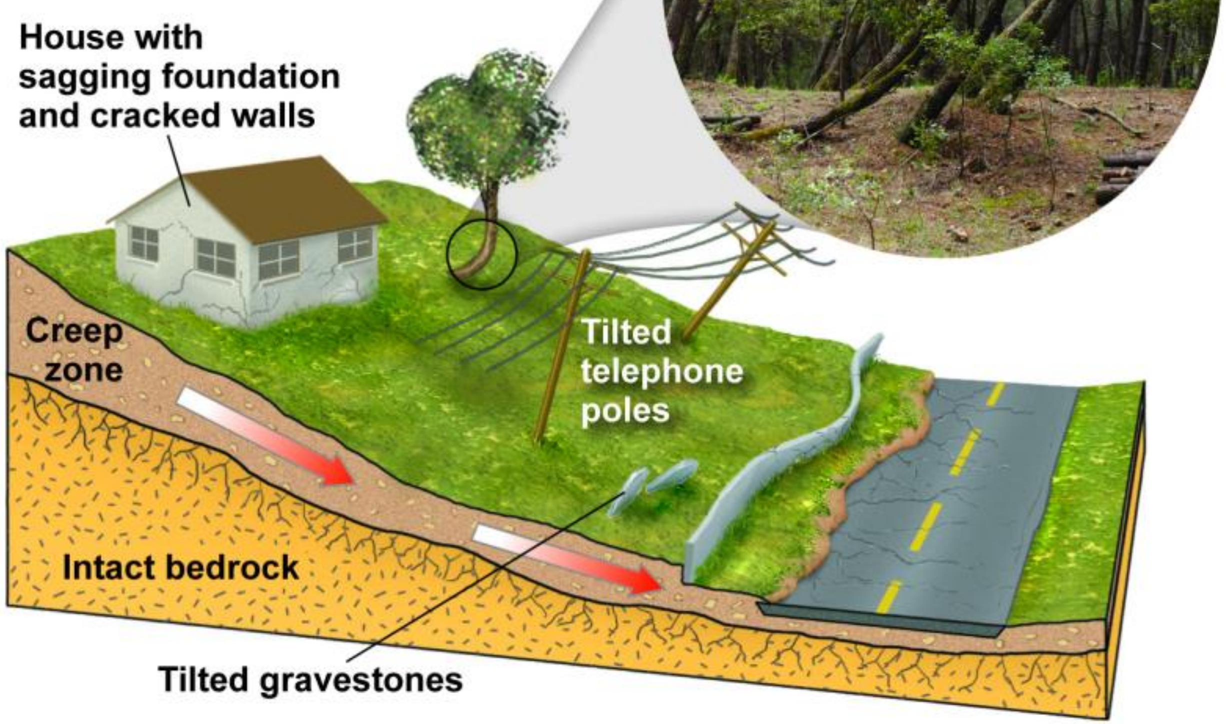
- Creep—slow downhill movement of regolith
  - Due to seasonal soil expansion and contraction
    - Wetting and drying
    - Freezing and thawing
    - Warming and cooling
  - Grains are moved:
    - Perpendicular to slope upon expansion
    - Vertically downward by gravity upon contraction





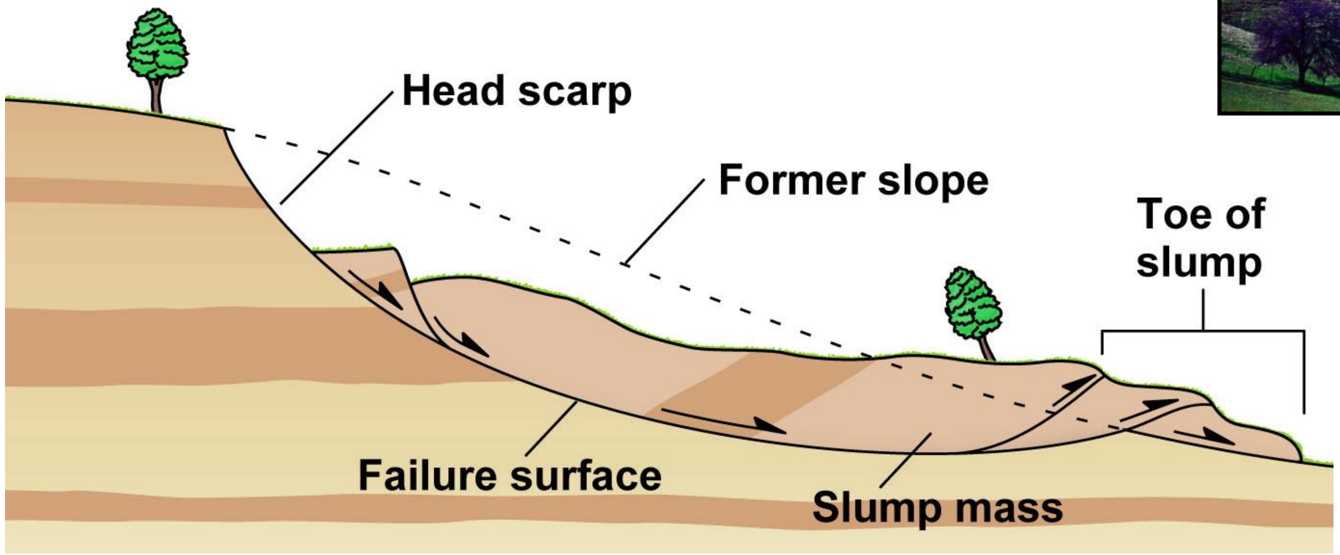
Types of Mass Movement

- Creep is evident from tilting of landscape features.
  - Trees
  - Telephone poles
  - Retaining walls
  - Foundations
  - Tombstones



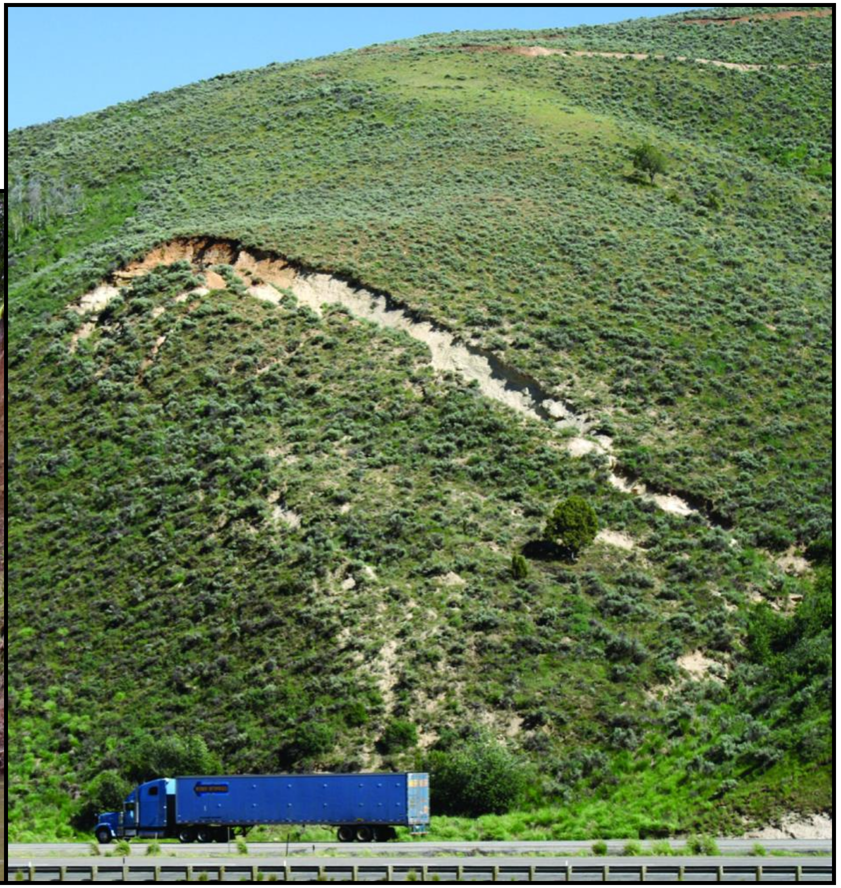
Types of Mass Movement

- **Slumping—sliding of regolith as coherent blocks**
  - Slippage occurs along a spoon-shaped “failure surface.”
  - Display a variety of sizes and rates of motion.
  - Slumps have distinctive features:
    - Head scarp—upslope cliff face
    - Toe—material at base
    - Discrete faulted slices



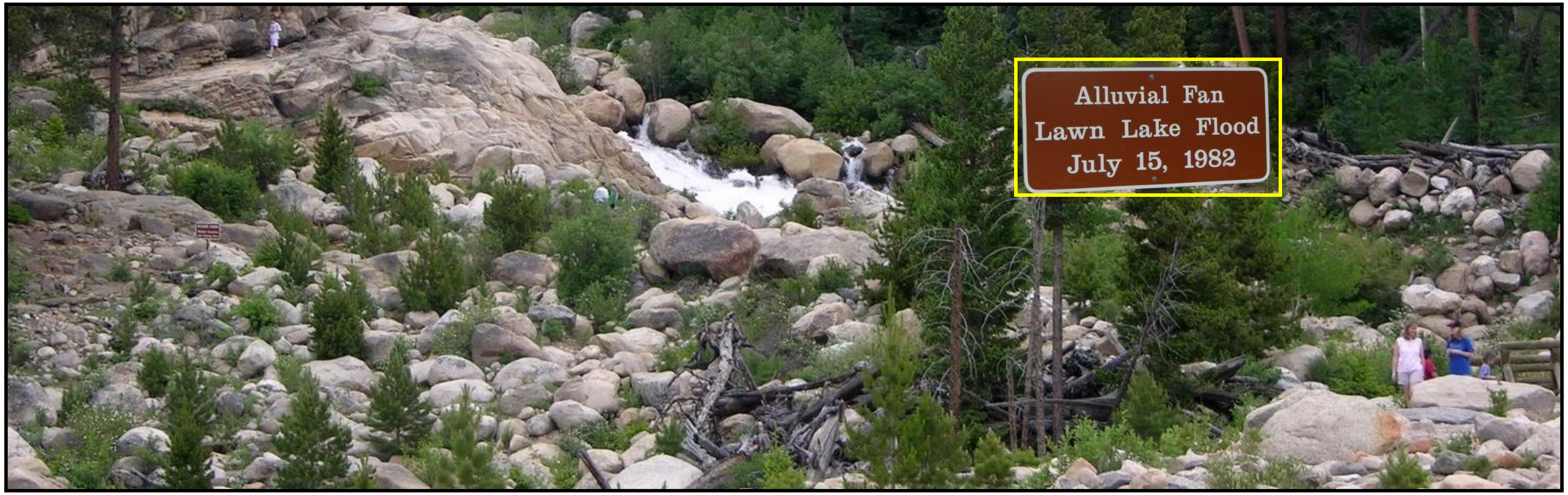
Types of Mass Movement

- Slumps are common along seacoasts & river cut banks.
  - Blocks that fall into water are often quickly eroded.
- Slumps can move slowly.
  - Can observe them develop
  - Reduces potential harm



Types of Mass Movement

- Mudflows, debris flows, and lahars—H_2O-rich movement
  - Move at a variety of speeds
    - Faster—more water or steeper slope angle
    - Slower—less water or lower slope angle
  - Tend to follow river channels down valley
  - Spread out into a broad lobe at the base of the slope
  - Able to carry huge boulders, houses, and cars

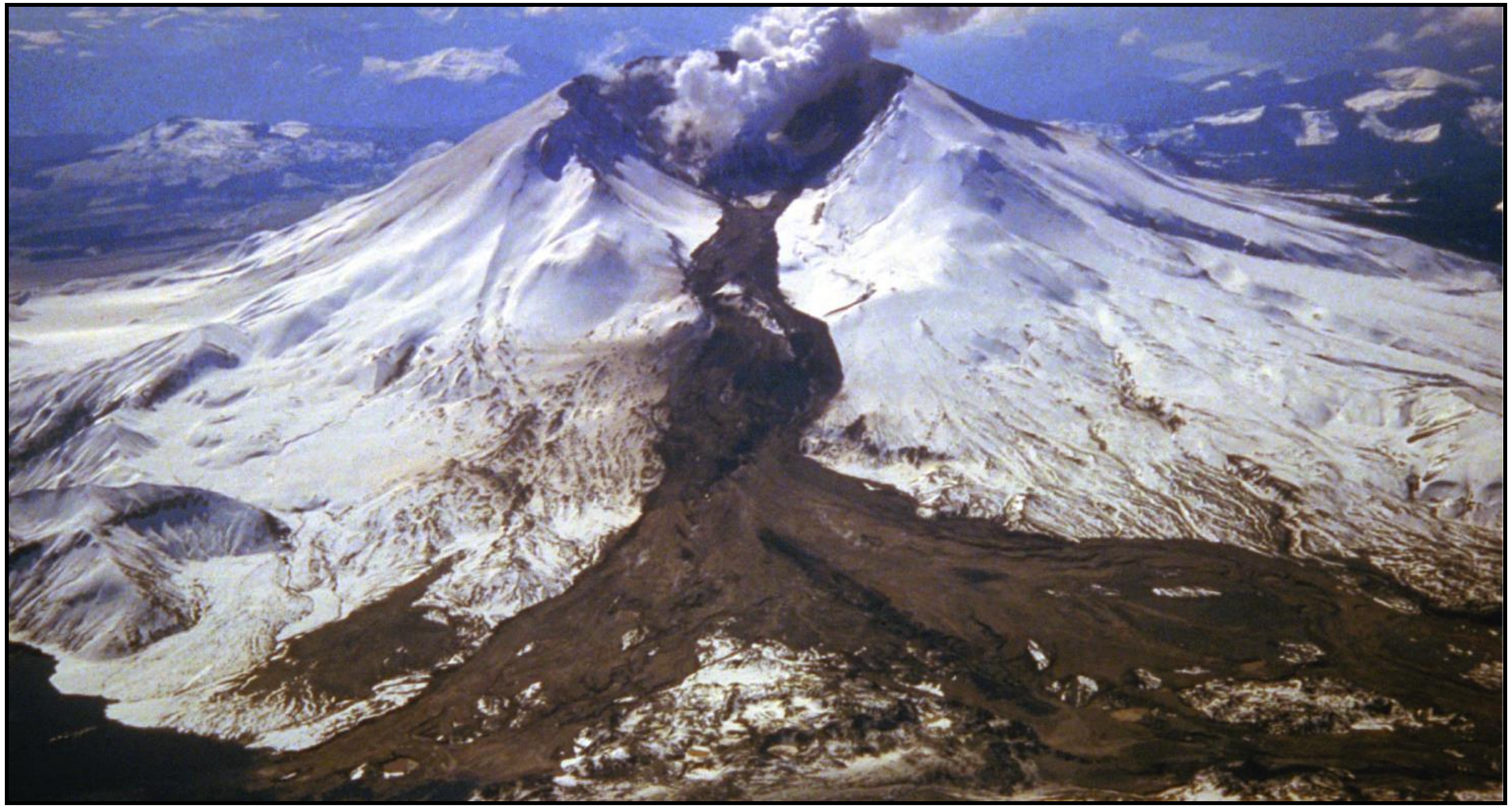


Types of Mass Movement

- Mudflows, debris flows, and lahars—H_2O-rich movement
  - Mudflow—a slurry of water and fine sediment
  - Common in tropical settings with abundant rainfall

Types of Mass Movement

- Mudflows, debris flows and lahars—H_2O-rich movement.
  - Lahar—a special volcanic mud or debris flow
    - Volcanic ash (recent or ongoing eruptions) mixes with:
    - Water from heavy rains or melted glacial ice.



Types of Mass Movement

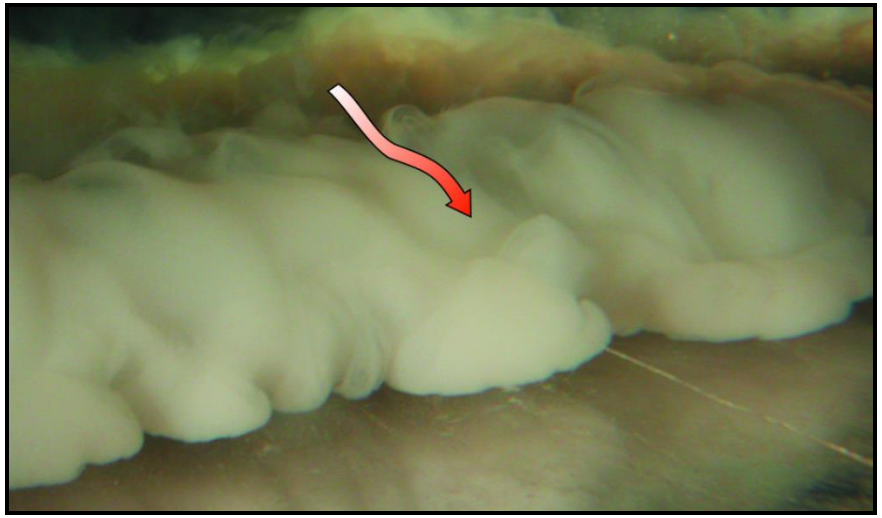
- Rock and debris slides—sudden movement downslope
  - Rock slide—a slide consisting of rock only
  - Debris slide—a slide comprised mostly of regolith
    - Movement down the failure surface is sudden and deadly.
    - Slide debris can move at 300 km per hour on a cushion of air.

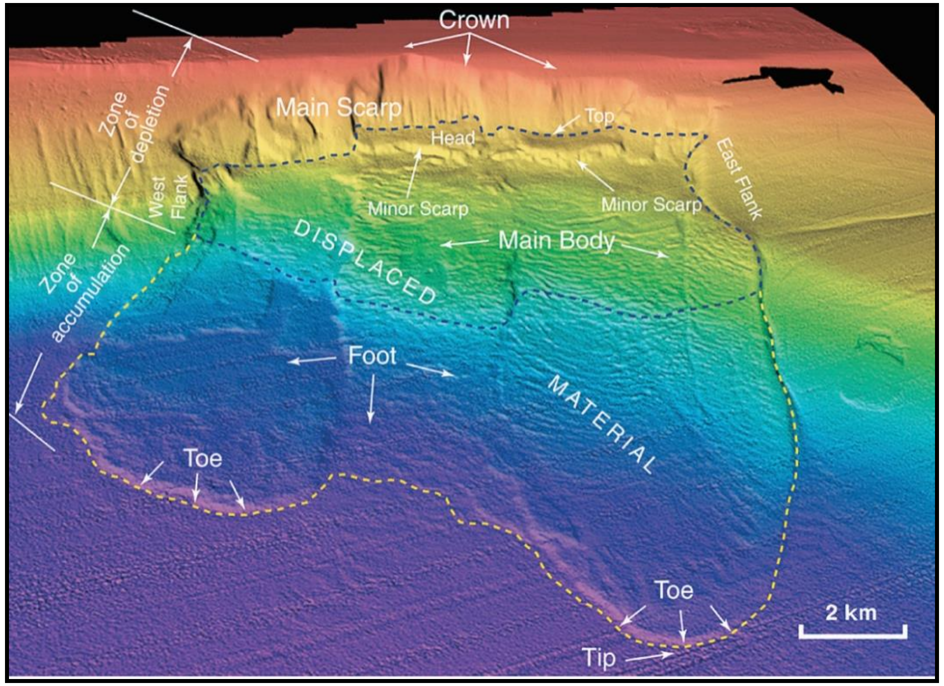
Types of Mass Movement

- Avalanches—turbulent clouds of debris and air
  - Snow avalanche—oversteepened snow that detaches
  - Move downhill with enormous force that flattens forests
  - Tend to reoccur in clearly defined avalanche chutes
  - Lethal to people caught in the way

Types of Mass Movement

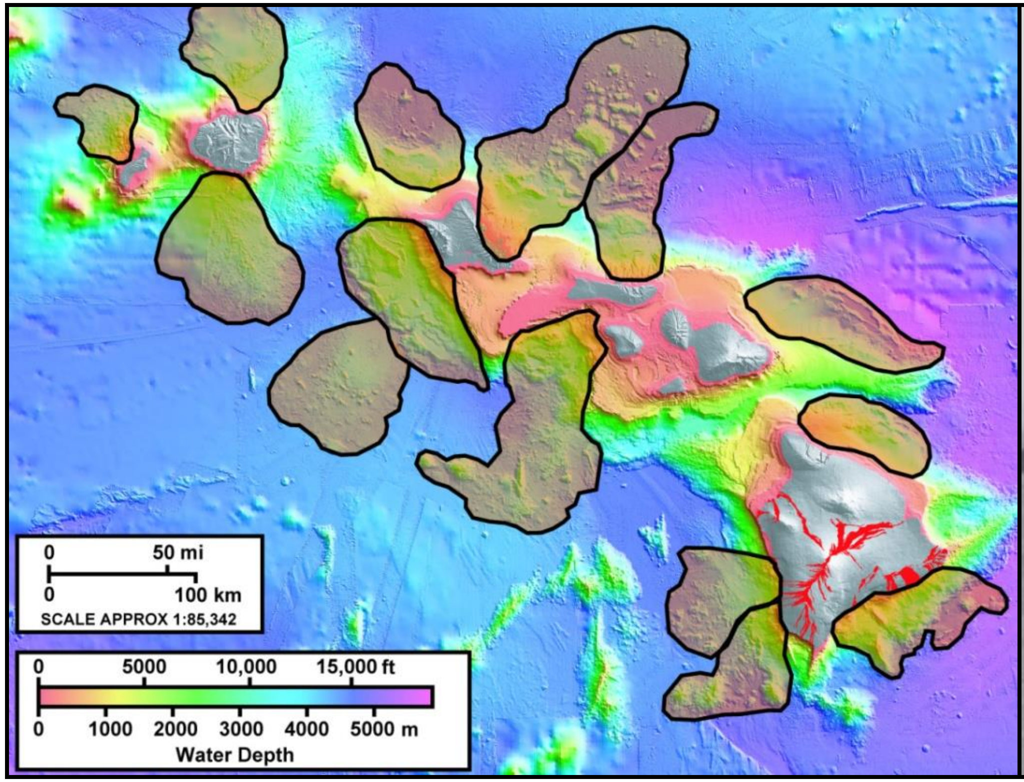
- Submarine mass movements often preserved by burial
  - Three types—based on degree of disintegration:
    - Submarine slumps—semicoherent blocks break and slip
    - Submarine debris flows—broken material moves as a slurry
    - Turbidity currents—sediment moves as a turbulent cloud
  - May be extremely large.





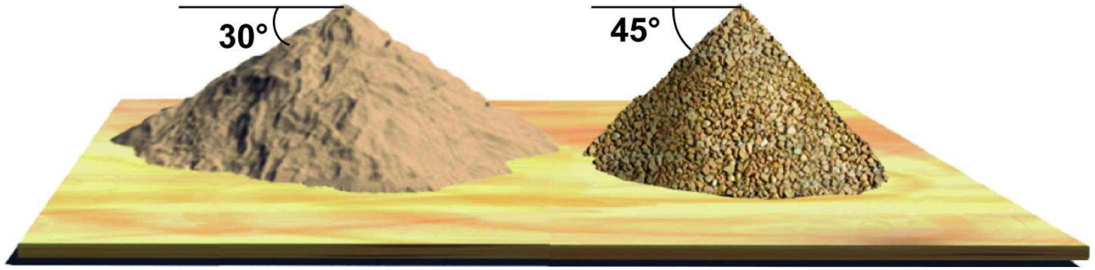
Types of Mass Movement

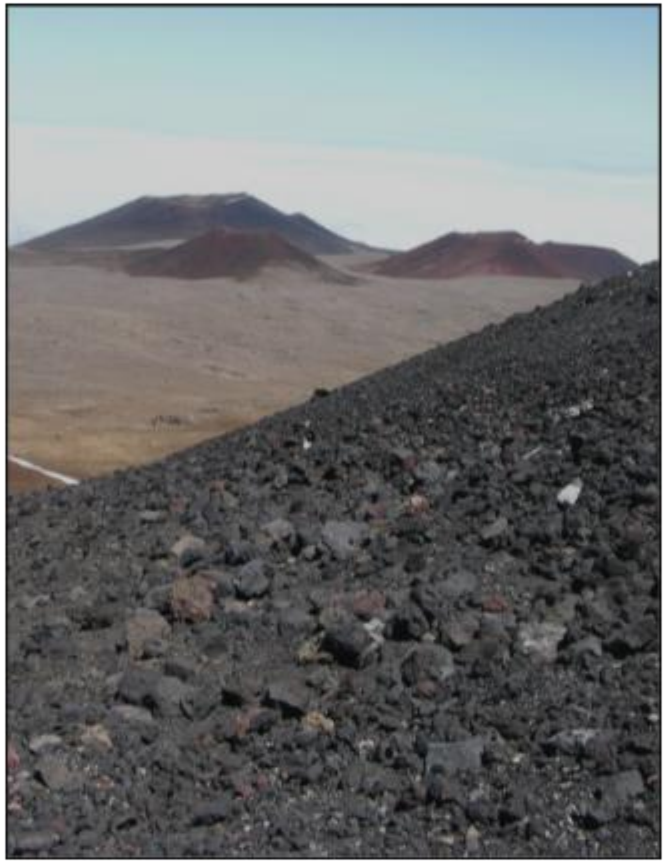
- Gigantic submarine mass movements are documented.
  - Much larger than land-based mass movements
  - An important process for shaping land in tectonic settings
  - Mass movements tied to catastrophic tsunamis



Slope Stability

- Loose granular material assumes a slope angle.
  - "Angle of repose" is a material property due to:
  - Particle size and shape and the surface roughness.
  - Typical angles of repose:
    - Fine Sand: 35º
    - Coarse Sand: 40º
    - Angular Pebbles: 45º





Why Do Mass Movements Occur?

- Shocks, vibrations, and liquefaction
  - Ground vibrations decrease material friction.
  - On an unstable slope, the downslope force takes over.
  - Vibrations are common.
    - Motion of heavy machinery or trains
    - Earthquakes
  - Vibrations can cause saturated sediments to liquefy.

Why Do Mass Movements Occur?

- Changes in slope strength
  - Weathering—creates weaker regolith.
  - Vegetation—stabilizes slopes. Removing vegetation:
    - Greatly slows removal of excess water
    - Destroys an effective stapling mechanism (roots)
    - Slope failures common after forest fires destroy vegetation


Oso Washington Mudslide 29 March 2014 aerial view {photo by Spc. Samantha Ciaramitaro)

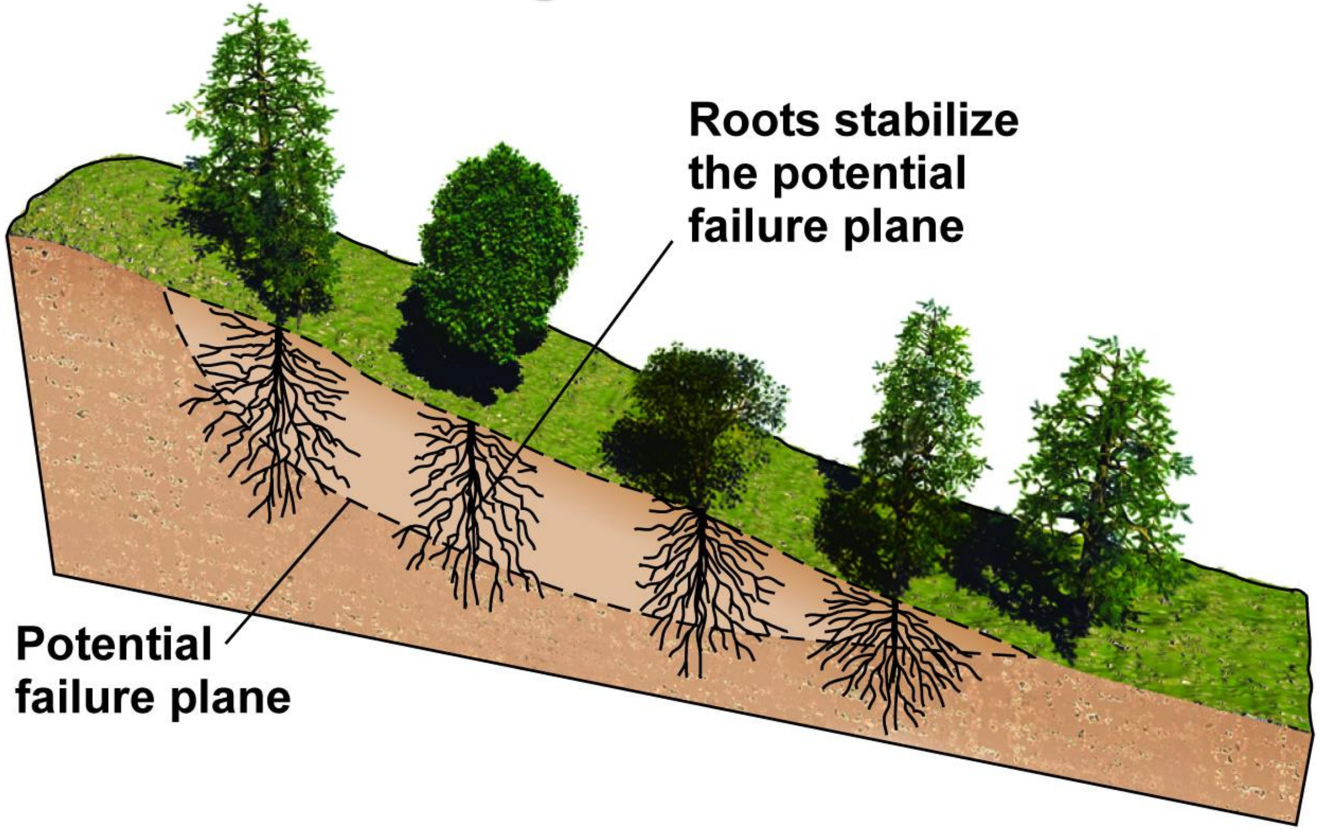
The Oso Washington mudslide north-east of Seattle killed 43 people

Protecting Against Mass Movement

- **Landslide potential mapping.**
  - **Identifies areas of potential risk that may not show signs.**
  - **Assesses multiple factors:**
    - **Slope steepness**
    - **Strength of substrate**
    - **Degree of water saturation**
    - **Orientation of planar features**
      - **Bedding**
      - **Joints**
      - **Foliation**
    - **Vegetation cover**
    - **Heavy rain potential**
    - **Undercutting potential**
    - **Earthquake probability**

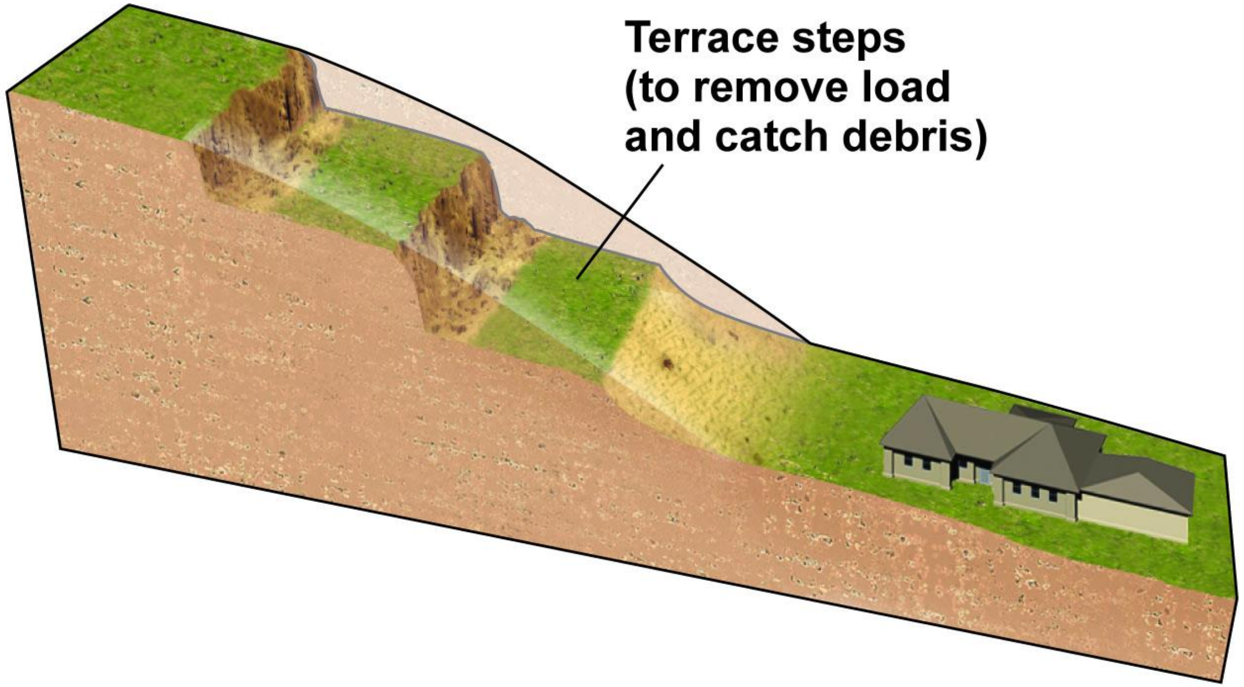
Preventing Mass Movements

- Action can reduce mass-movement hazards.
  - Revegetation—adding plants has two positive effects:
    - It removes water by evapotranspiration.
    - Roots help to bind and anchor regolith.



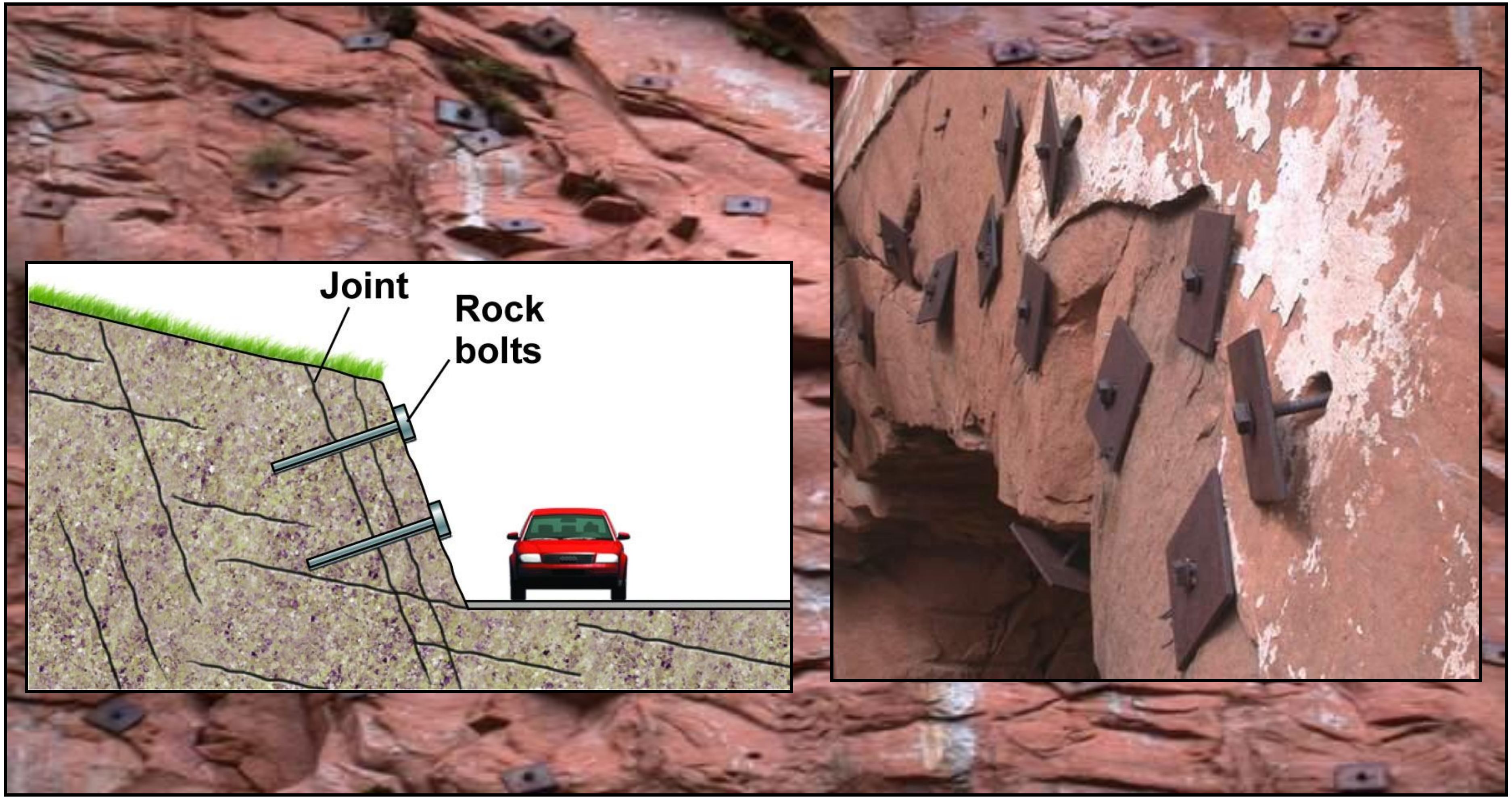
Preventing Mass Movements

- Action can reduce mass-movement hazards.
  - Redistributing mass by terracing.
    - Removes some of the mass loading a slope.
    - Catches debris.



Preventing Mass Movements

- Engineered structures
  - Rock staples—rods drilled into rock to hold loose facing.



Preventing Mass Movements

- Engineered structures
  - Avalanche sheds—structures that shunt avalanche snow
- Controlled blasting—surgical removal of dangerous rock