Indian Institute of Technology, Kanpur

Department of Earth Sciences

ES0213A: Fundamentals of Earth Sciences

Lecture 01. Course Introduction

Santanu Misra
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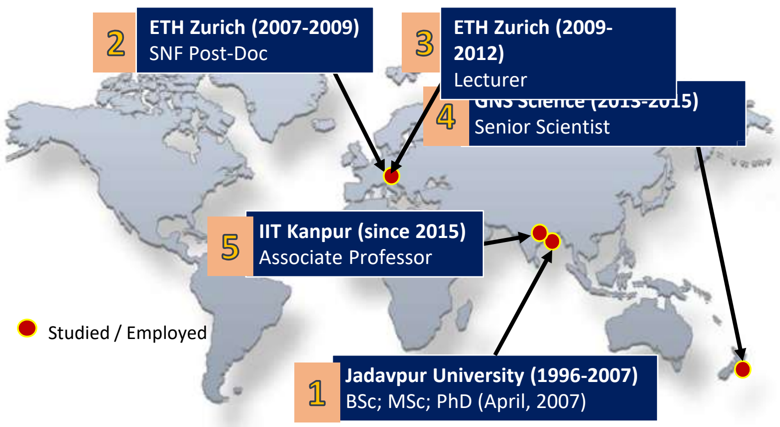
Experimental Rock Deformation Laboratory

IITK

Your Instructor



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Experimental Rock Mechanics / Rock Physics

- Strength, failure mechanism and mechanical anisotropy.
- Fracture Mechanics related to Earthquake generation.
- Experimental wave-propagation, micro-seismicity.
- Porosity, permeability and fluid flow.

Structural Geology / Tectonics

- Tectono-Metamorphic evolution of Subduction interface.
- Fluid flow during crustal deformation.
- Microstructure / Texture analysis.

Teaching Assistants

Mr. Abinash Bal
Office: 109C, Old SAC
E-mail: *abinash@iitk.ac.in*

Joined IIT Kanpur in 2018
M. Sc. 2018, IIT Bombay, Maharastra

Mr. Anamitra Sikdar
Office: 109C, Old SAC
E-mail: *asikdar@iitk.ac.in*

Joined IIT Kanpur in 2019
M. Sc. 2018, Jadavpur University, Kolkata

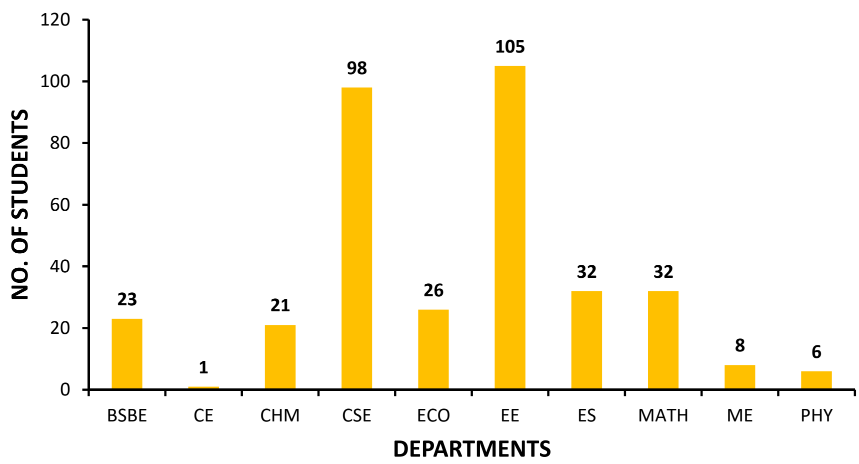
About You

A teacher doesn't like a class without any student in the classroom. This is a changed time… anyway. Let's learn ONLINE !

- All of you must be *exceptionally sharp!*
- If you're worried about whether you can handle the class…. Relax !!
- Many of you are here to fulfill the "ESO" course requirement in your template, and therefore, not very serious about the learning. That's OK!
- There is no such thing as a "science student" *vs.* a "non-science student (engineering)"! You were BORN curious – which is what science really is all about – investigating the world.

Class Statistics

Total Number of Students: 352



Y19 : 302
Y18 : 47
Y17 : 1
Y16 : 1
Y14 : 1

First Assignment (ungraded)

Please see the Google form uploaded/shared in the class mail

- Your Name
- Your Roll Number
- Your Department
- The reason(s) for registering the class
- What surprises you most about the Earth?
- What is the craziest thing you have ever done so far?
- What is(are) the place(s) in Earth that you wish to travel one day?

https://forms.gle/t6XqMhR45sP4UCdb9

You MUST submit the form on or before 5th September, 2020; 11:55 PM

Class Management

Please go through the following links for the general instructions:

IITK Senate Decisions:

https://www.iitk.ac.in/doaa/data/senate_decisions_implementation_2020_21_I.pdf

FAQ about the courses:

https://www.iitk.ac.in/doaa/data/senate_decisions_implementation_2020_21_I.pdf

Technical requirements:

https://www.iitk.ac.in/doaa/data/Technical_Infrastructure_Requirements.pdf

Class Management

- Online classes
- The primary teaching platform is: https://hello.iitk.ac.in. [any alteration of this platform will be communicated to you well in advance].
- Pre-recorded lectures of ~90-110 mins/week will be uploaded on Friday of the previous week. Individual lectures will be of short duration.
- The lecture presentations (.pdf) and other related study-materials will also be uploaded in the online platform.
- There will be one or more discussion (interaction) sessions/week as per the schedule in the time table. We shall use Zoom online platform for the discussion.
- All assignments/quizzes will be conducted online

Scheme of the Grades

Discussions (your participations in the discussions, overall engagement including attendance)	**10%**
Assignments and Quizzes (Best 70% of your assignments and 100% of the quizzes)	**25%**
Mid Semester Examination (Online) (MCQ; Short conceptual Questions – Open Book)	**25%**
End Sem Examination (Online) (MCQ; Short conceptual Questions – Open Book)	**40%**

If you cannot follow the lectures because of sickness, poor internet connections or for any other reasons, please contact me ASAP.

Policies on Cheating and Ethics

Cheating in any form in NOT ALLOWED.

If a student cheats or uses unfair means in a course,

- The student will get an **F** grade in the course.
- The student cannot drop the course.
- DUGC of the concerned department will be informed
- A complaint will be sent to SSAC for action.

https://web.iitk.ac.in/july14dosa/data/SSAC-procedures-and-Guidelines.pdf

Content of this lecture-series

Solar System and Earth; The primitive Earth; Geological Time scale; Origin of life and major geological events; Numerical Dating. Rocks, minerals and soils; Plate Tectonics and Mountain building; Deformation and Geodynamics; Earthquakes, Volcanoes. Earth, Ocean, Land, Rivers, Atmosphere, Biosphere, Cryosphere and Climate; Energy budget; Carbon Cycle; Hydrological Cycle; Weathering and erosion. Coupled processes in Earth System; climate change, Geological resource (minerals, hydrocarbons and water); Sustainability and Anthropocene activities.

General TIME TABLE

Orientation [illegible]	[illegible]
Registration and Fee Payment for All New Students in the MTech, MDes, MSR, MBA, MSc 2-Yr, MS-PD and PhD Programmes	Aug 27-28, 2020
Registration and Fee Payment for **Continuing Students** in all Programmes	Aug 29-30, 2020
Late Registration	Sep 5, 2020
Classes and Add/Drop Schedule	
Release of First Course Handout	Aug 29-30, 2020
Online Classes Commence	Sept 1, 2020
Adding a Course	Sept 1-7, 2020
Dropping/De-registering Modular Courses (First Half)	Sept 26, 2020
Classes for the Modular Courses (First Half) End	Oct 10, 2020
Classes for Modular Courses (Second Half) Commence	Oct 19, 2020
Last date for Dropping Regular Courses	Oct 31, 2020
Last date for De-registration in Regular Courses	Nov 7, 2020
Dropping/De-registering Modular Courses (Second Half)	Nov 16, 2020
Online Classes End	Nov 30, 2020
Academic Pre-registration (2020-21-II)	
Academic Pre-registration for 2020-21-II	Nov 16-23, 2020
Examinations and Grade Submission	
Mid-Semester Examination (Online)	Oct 12-18, 2020
End Semester Examination (Online)	Dec 3-12, 2020
Make-up Examination (Online)	Dec 16-19, 2020
Last date for End Semester Grade Submission	Dec 20, 2020
Last date for Make-up Grade Submission and Conversion of I Grades	Dec 22, 2020
Vacation	

Class TIME TABLE

Weeks	Dates	GENERAL TOPICS
Week_01	Sept 01- Sept 04	General Introductions
Week_02	Sept 07 - Sept 11	Earth as a System and Principles **[QUIZ - I]**
Week_03	Sept 14 - Sept 18	Plate Tectonics
Week_04	Sept 21 - Sept 25	Minerals and Rocks **[QUIZ - II]**
Week_05	Oct 05 - Oct 09	Deformation of Rocks
Week_06	Oct 12 - Oct 16	MID SEMESTER EXAMINATION
Week_07	Oct 19 - Oct 23	History of the Earth and Time Scale
Week_08	Oct 26 - Oct 30	Earth's interior **[QUIZ - III]**
Week_09	Nov 02 - Nov 06	Natural Hazards (Earthquakes, Volcanisms)
Week_10	Nov 09 - Nov 13	Climate and Atmosphere
Week_11	Nov 16 - Nov 20	Landforms, Weathering and Erosion **[QUIZ - IV]**
Week_11	Nov 26 - Nov 30	Earth's resources (water, minerals, hydrocarbons) and Human Impact
Week_12	Dec 3 - Dec 12	END SEMESTER EXAMINATION

Tentative Class TIME TABLE

Weeks	Dates	GENERAL TOPICS
Week_01	Sept 01- Sept 04	General Introductions
Week_02	Sept 07 - Sept 11	Earth as a System and the Principles of Earth
Week_03	Sept 14 - Sept 18	Plate Tectonics
Week_04	Sept 21 - Sept 25	Minerals and Rocks
Week_05	Sept 28 - Oct 02	Deformation of Rocks (Strain & Stress)
Week_06	Oct 05 - Oct 09	Basic Structures of Rocks
Week_07	Oct 12 - Oct 18	MID SEMESTER EXAMINATION
Week_08	Oct 19 - Oct 23	History of the Earth and Time Scale
Week_09	Oct 26 - Oct 30	Earth's interior
Week_10	Nov 02 - Nov 06	Natural Hazards (Earthquakes, Volcanisms and others)
Week_11	Nov 09 - Nov 13	Climate and Atmosphere
Week_11	Nov 16 - Nov 20	Landforms, Weathering and Erosion
Week_12	Nov 23 - Nov 27	Earth's resources (water, minerals, hydrocarbons) and Human Impact
Week_13	Dec 3 - Dec 12	END SEMESTER EXAMINATION

4-5 Quizzes; shall announce the dates on the 2nd week

Summary of this lecture

This is a large class with students from various disciplines.

Please respect the conduct of the course and your colleagues.

The course is being offered online, which is a new platform to all of us. Be patient, please, if there is any technical fault.

Participate in the course and respond timely.

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ES0213: Fundamentals of Earth Sciences

Experimental Rock Deformation Laboratory

Lecture 02. Subject Introduction

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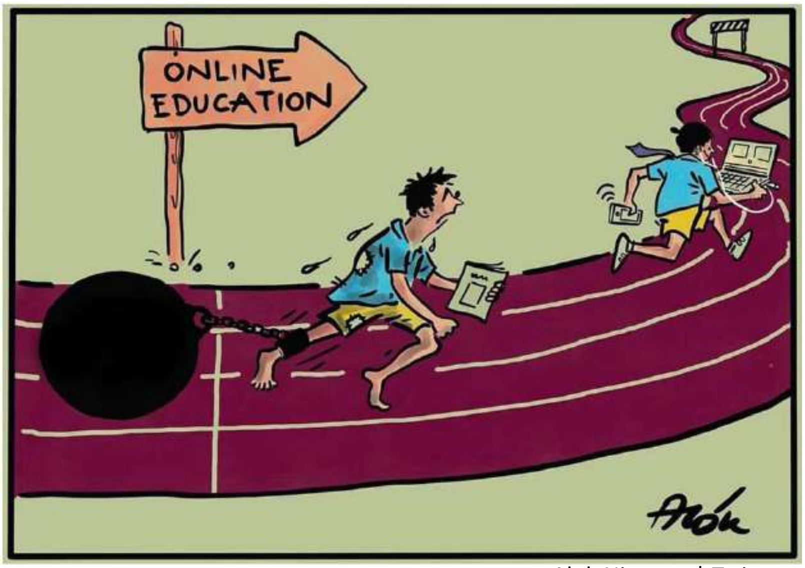
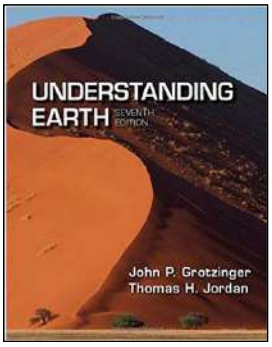
ONLINE CLASSES

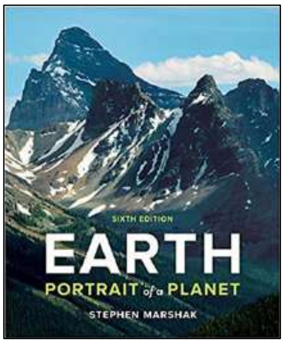


Alok Nirantar | Twitter

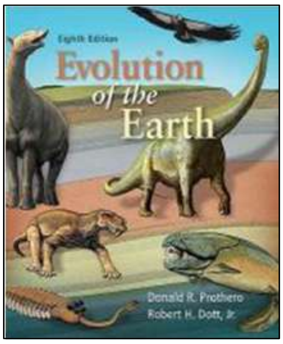
Study Materials



J. Grotzinger and T. Jordan, Understanding Earth, 2010 (7th Ed.), W.H. Freeman & Company: ISBN-13: 978-1-4641-3874-4



Stephen Marshak, Earth: Portrait of a Planet, 2015 (5th Ed.), W. W. Norton & Company: ISBN-13: 978-0393937503.



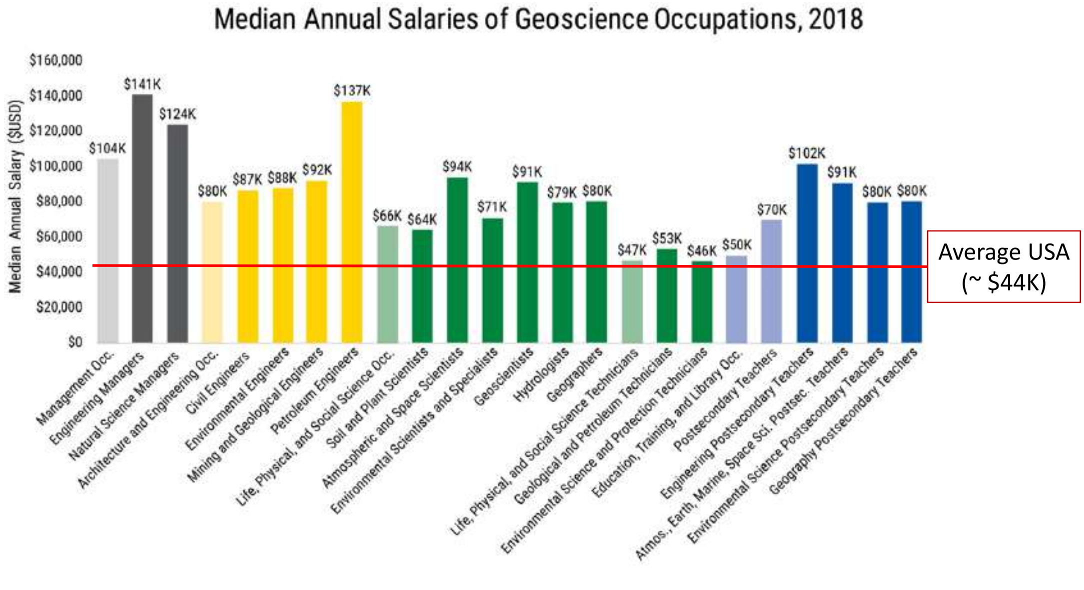
D. R. Prothero and R. H. Dott, Jr. Evolution of the Earth. 2010 (8th Ed.), McGraw Hill, 576 p.

Most of the materials of this course are from these books; also from my own collections and from different teaching sites and blogs.

Earth Sciences… what is that?

- Earth Science is a strongly interdisciplinary subject with several links to fundamental science pillars like Physics, Chemistry, Mathematics and Biology.
- The subject links important resources such as minerals, energy, and water, as well as to hazards and environmental management.
- Over the years, this discipline has developed into a major knowledge domain of science and technology due to the advent of modern space observation systems, new exploration technologies for probing earth's surface and sub-surface for resources, and the development of sophisticated geochemical analytical methods.
- In addition, several important issues such as climate change, natural hazards, environmental degradation and resource depletion have made this science highly relevant to the society.

Earth Sciences… what about the job market?



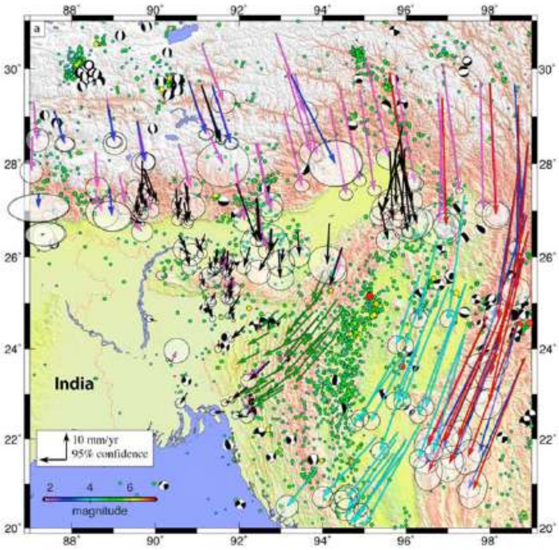
AGI Geoscience Workforce Program; Data derived from the U.S. Bureau of Labor Statistics, Occupational Employment Statistics 2018

Some basic concepts and ideas in Earth Sciences

- Earth scientists (Geologists) use observations and testable ideas to understand and explain our planet. This is the basic of practicing SCIENCE.
- Earth is ~4.6 billion years old. That's 4,600,000,000 years!
- Earth is a complex system of interacting rock, water, air, and life.
- Earth is continuously changing; Life evolves on a dynamic Earth and continuously modifies the Earth.
- The changes in earth are extremely slow; sometimes very fast.
- Earth is magnetic and has a geodynamo system.
- Earth is a water planet.
- Humans significantly alter the Earth.

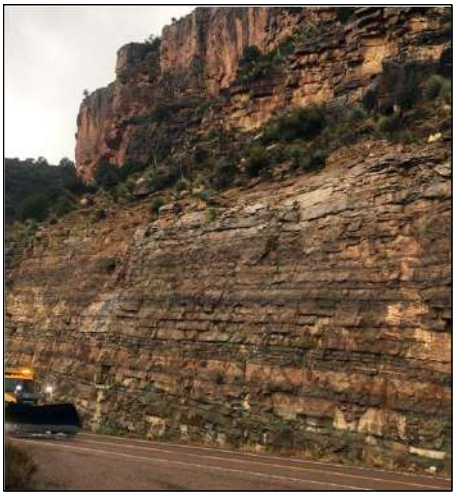
Some basic concepts and ideas in Earth Sciences

Geologists use observations and testable ideas to understand and explain our planet.



Some basic concepts and ideas in Earth Sciences

Earth is ~4.6 billion years old. That's 4,600,000,000 years!



Lunar Sample (67215)	: 4.46 billion years
Jack Hills (Australia)	: 4.38 billion years
Greenstone Belt (Canada)	: 4.28 billion years
Alan Hills (Antarctica)	: 4.09 billion years

Oldest rock in India: 4.24 billion years old (Kendujhar, Odisha)

Some basic concepts and ideas in Earth Sciences

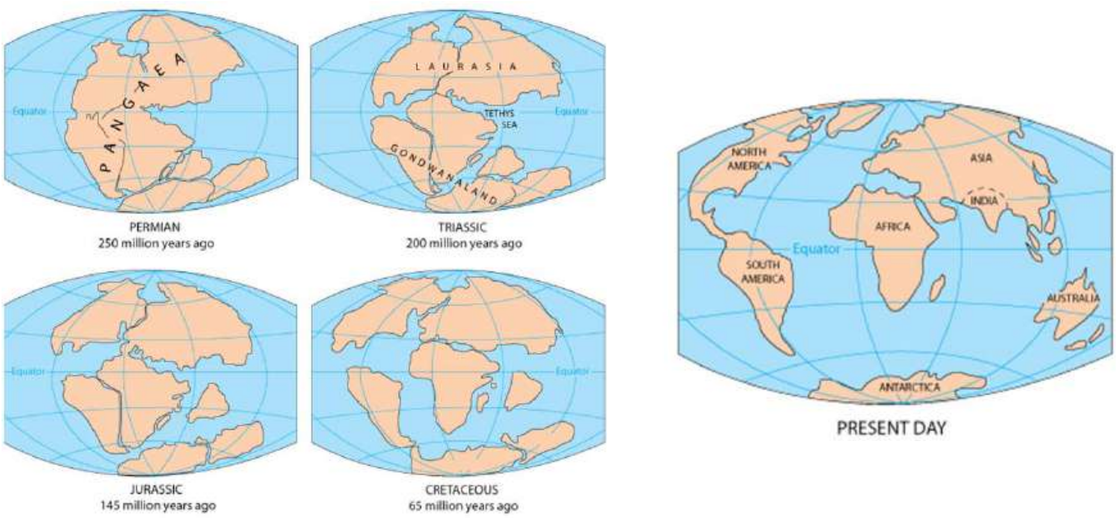
Earth is a complex system of interacting rock, water, air, and life.

Dust plumes from Iran, Afghanistan and Pakistan blow southward over the Arabian Sea, Dec. 28, 2012. Credit: NASA / Goddard / MODIS Land Rapid Response.

North Atlantic phytoplankton bloom off the coast of Iceland, June 24, 2010. Credit: NASA's Earth Observatory.

Some basic concepts and ideas in Earth Sciences

Earth is continuously changing; so the LIFE on Earth



Some basic concepts and ideas in Earth Sciences

The changes in earth are extremely slow; sometimes very fast.

The most recent layer of sediment is about 250 million years old.

The rocks at the bottom of the Grand Canyon are 1.7–2.0 billion years old.

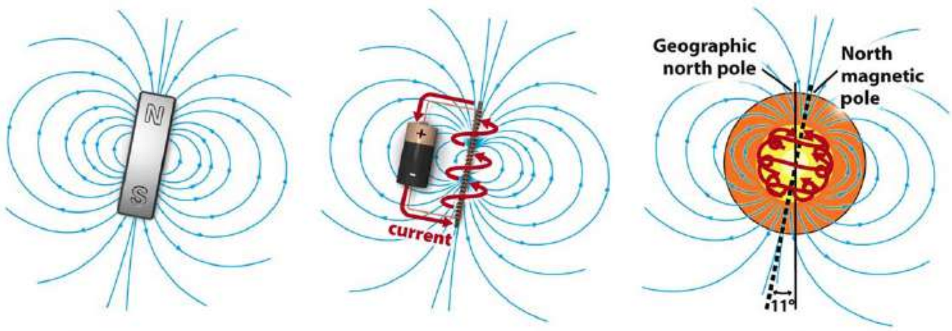
The explosive impact of a meteorite created this 1.2-km-wide crater in just a few seconds.

Earthquake,
Landslide,
Avalanches,
Volcanoes….

Some basic concepts and ideas in Earth Sciences

Earth is magnetic and has a geodynamo system

Rapid motion of the liquid outer core stirs up electrical flow in the solid (iron) inner core, causing Earth's magnetic field.



(a) Bar magnet (b) Electromagnetic (c) Geodynamo

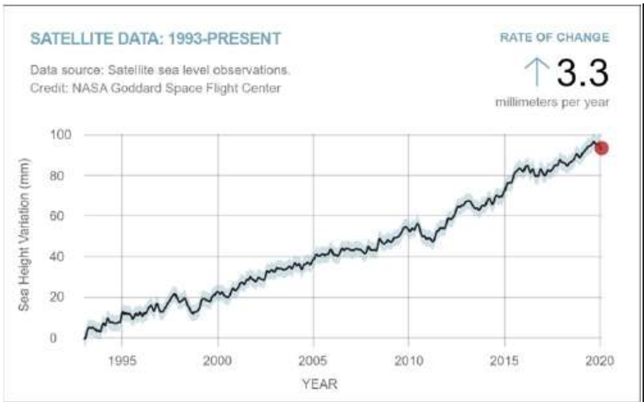
Some basic concepts and ideas in Earth Sciences

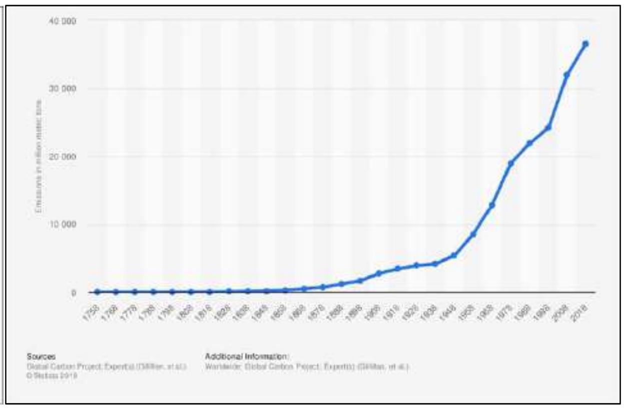
Earth is the water planet

About 71% of the Earth's surface is water-covered, and the oceans hold about 96.5 % of all Earth's water. Water also exists in the air as water vapour, in rivers and lakes, in icecaps and glaciers, in the ground as soil moisture and in aquifers, and even in us.

Some basic concepts and ideas in Earth Sciences

Humans significantly alter the Earth





Assignment – 01 (graded)

- Do we also have water inside the earth? If yes, how and in which form?
- Suggest three major human activities which are (has been) altering the earth.
- Suggest three slow and three fast natural processes that can affect the Earth's dynamics.
- Not every planet has a geodynamo, why? Earth did not have a magnetic field, what might be different about our planet?

Summary of this lecture

Understanding the Earth and its different processes are important. In this course, we'll learn the basics of how to look at the system.

Next lectures

Origin of the Universe and the Solar System

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ES0213A: Fundamentals of Earth Sciences

Lecture 03. Origin of the Universe

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Experimental Rock Deformation Laboratory

Aims of this lecture

Concept of Scale and Time

Origin and the Universe

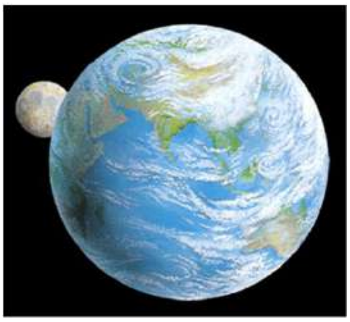
The Earth

We pass our lives on our one planet Earth.

Earth may seem endless; it isn't.

Viewed from space, Earth is a small, shiny globe.

It is truly our island oasis in space.

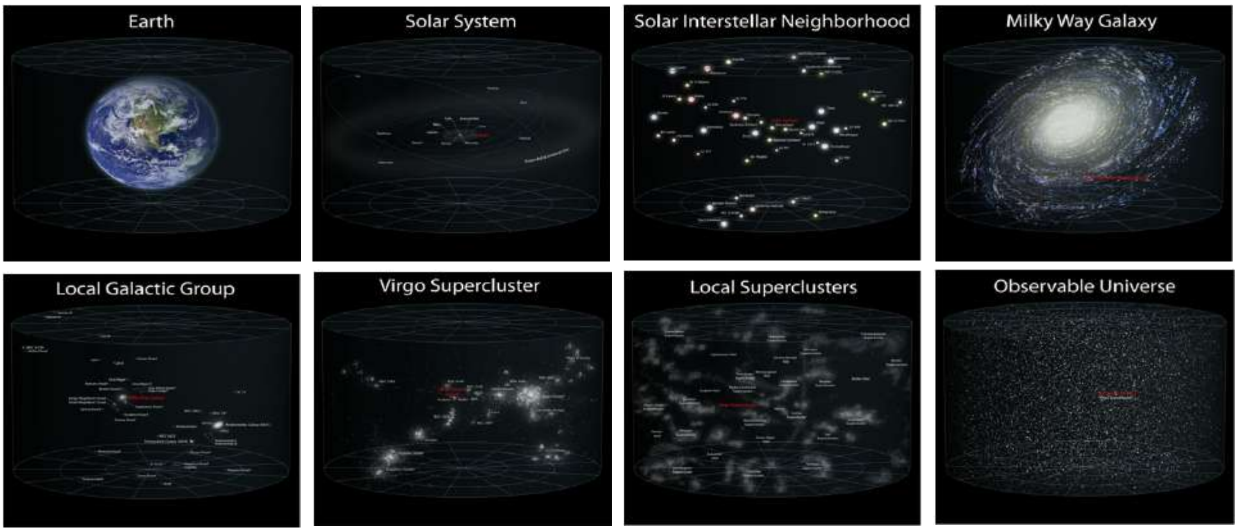


The Earth is a very special and unique planet.

- Its temperature, composition and atmosphere favor life.
- It is dynamic and ever-changing.
- It has a long and complex history

Where is our place in the space, actually?

Concept of Scale



Courtesy: Andrew Z. Colvin, Arizona State University

Concept of Scale

https://htwins.net/scale2/

[View of the universe from the Planck Length to the Universe]

Concept of Time

- If we were to compress the time since the beginning of the universe into one year, and set the first time at January 1st -
  - MID MARCH: Milky way Galaxy formed
  - END AUGUST: Sun and Solar System formed
  - MID SEPTEMBER: Earth Formed
  - END SEPTEMBER: First Life
  - 26th DECEMBER: First Mammal
  - 31st DECEMBER (22:24): Early Human, Stone tools and weapons
  - 31st DECEMBER (23:54): *Homo sapiens* (Modern Human)

Concept of Time

13.7 billion years ago – origin of the universe
4.6 billion years ago – formation of solar system and Earth
3.5 billion years ago – formation of geodynamo; first known fossils (bacteria)
2.7 billion years ago – oxygen begins to build up in atmosphere
2.5 billion years ago – large continents in crust
2.0 to 1.0 billion years ago – more complex life, such as algae, evolved
600 million years ago – first animals
443 million years ago – first mass extinction of life
420 million years ago – first land mammals
359, 251, and 200 million years ago – mass extinctions of life
125 million years ago – first flowering plants
65 million years ago – last mass extinction (death of the dinosaurs and many other species)
5 million years ago – appearance of first hominids
200,000 years ago – appearance of *Homo sapiens*

Cosmology

Conscious thought distinguishes humans.

- Developed across thousands of generations.
- Lends us curiosity, insight, and the ability to learn.

As a result, we seek to explain our surroundings.

- Where do we come from?
- Where do we fit in the Universe?
- Why are we here?

Cosmology

Study of the structure and evolution of the Universe.

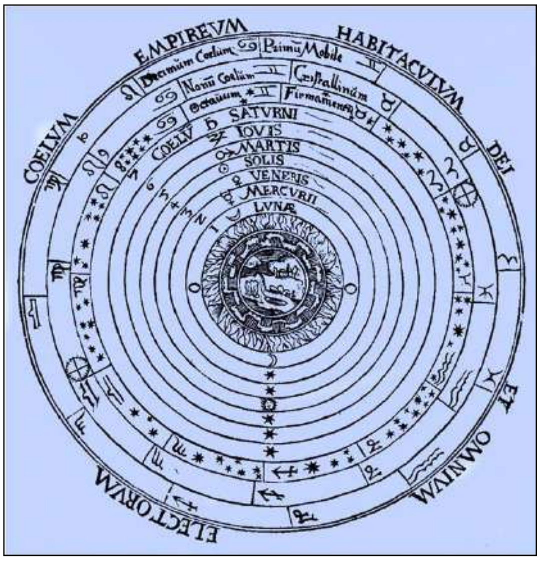
Cosmology is a complicated science.

- Requires thinking in unfamiliar scales of space and time.
  - Spatial scales.
    - Attometers (10^{-21} meters), to
    - 10s of billions of light years (9.46^{22} meters +).
  - Temporal scales.
    - Attoseconds (10^{-21} seconds), to
    - 10s of billions of years (3.15^{17} seconds +).

Ideas about the Universe have a rich history.

- These ideas are often culturally determined (and dominated).

The Earth Centered Universe



Universe as conceived of by **Aristotle** and **Ptolemy**.

The earth is in the center, does not revolve on its axis and composed of four elements: Earth, Water, Fire and Air. It is surrounded by ten concentric spheres made of a perfectly transparent substance known as "quintessence." These spheres revolve around the earth, carrying the other celestial bodies. As you can see, one is the sphere "of the Moon" ("Lunae"), two is Mercury ("Mercurii"), three is Venus ("Veneris"), four is the Sun ("Solis"), five is Mars ("Martis"), six is Jupiter ("Iovis"), seven is Saturn ("Saturni"), and spheres eight, nine and ten hold the "fixed stars“. Beyond the tenth sphere is, as the words in the periphery say in Latin, "The Kingdom of Heaven, the Abode of God and of the Elect."

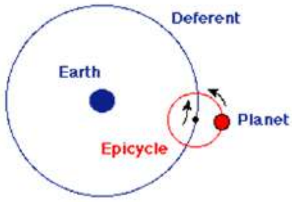
What is the problem of this model?

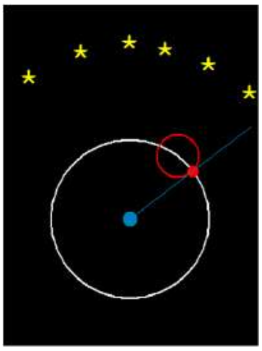
The problems of Earth Centered Universe

- Does not explain retrograde motion of planets

Retrograde motion of Mars in summer of 2003.
Image source: NASA

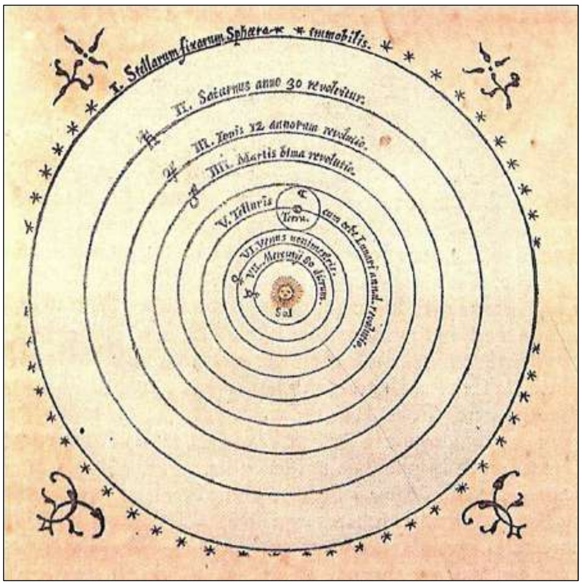
SOLUTION: Claudius Ptolemy





- Does not explain the changing brightness and phases of the planets

Sun Centered Universe

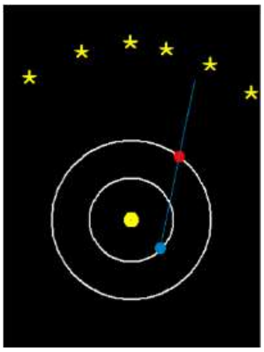


Through careful observation, **Nicolas Copernicus** noted a major problem with Ptolemy's model. The mathematical issue he noticed was that occasionally the planets would travel backwards through the sky. This is known as retrograde motion.

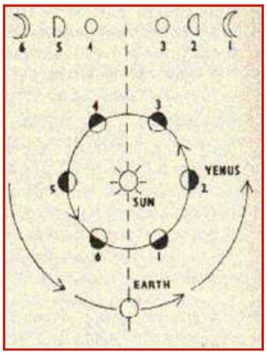
In 1514 after moving back to Poland, Copernicus distributed the first handwritten copies of his book to his friends. In his book he purposed that the Earth was not in ne center of the universe but instead the sun was. The principles of his sun-centered astronomy became known as ***heliocentric astronomy***. His book also stated that the rotation of the Earth around the sun accounted for the rising and setting of the sun, movement of the stars, and the changing season. Finally his book also explained that the Earth's motion through space caused the retrograded motion of the planets.

Sun Centered Universe

- Retrograde motion of planets (Nicolai Copernicus)



- Phase changes of planets (Galileo Galilei)



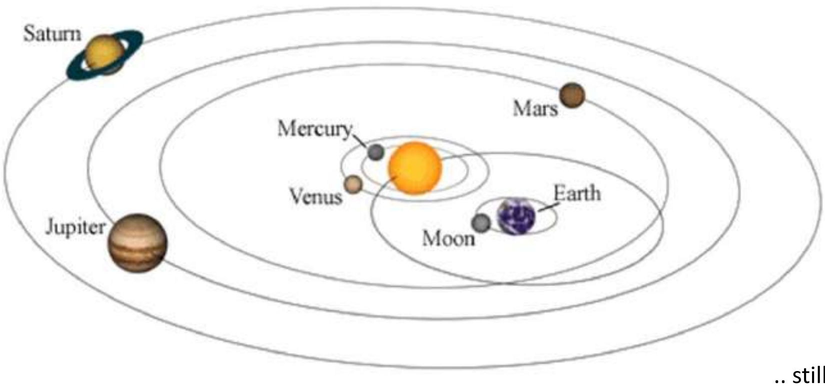
- Varying brightness of planets

.. automatically solves as the distance between the planets and the Earth varies with time.

- Note, the orbits of the planes are still CIRCULAR and the planets have uniform motion.
- Problems in predicting the future positions of planets.

Sun Centered Universe

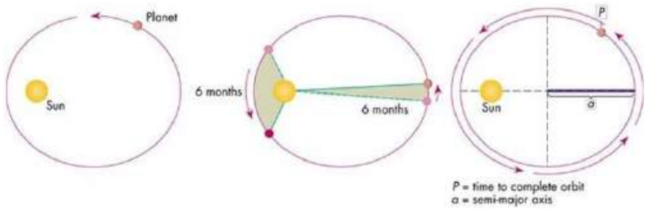
- **Tycho Brahe** proposed a model of the solar system to explain Galileo's observation that Venus has phases without making it necessary for Earth to be moving. His model had all the planets (except Earth) orbiting around the Sun, but then the Sun orbited around the Earth. This model satisfies ALL the observations because it corresponds to reality except that is viewed from the point of view of someone on Earth.



.. still, circular orbits

Sun Centered Universe

- Laws of planetary motion (1602) – Johannes Kepler [1571-1630]
  - FIRST LAW: The path of the planets about the sun is elliptical in shape, with the center of the sun being located at one focus. [The Law of ELLIPSE]
  - SECOND LAW: The orbital speed of a planet varies so that a line joining the Sun and the planet will sweep over equal areas in equal time intervals. [The Law of EQUAL AREAS]
  - THIRD LAW: The ratio of the squares of the periods of any two planets is proportional to the ratio of the cubes of their average distances from the sun. [The Law of HARMONICS]

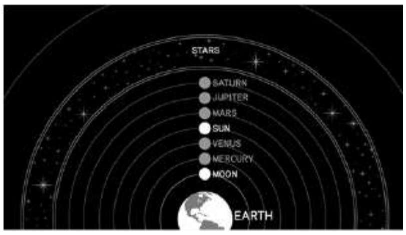


P^2 (years) ∞ α^3(AU)$= \frac{4\pi^2}{G(M_1+M_2)}\alpha^3$

- Observations support these laws, but WHY the laws should work was unknown.

The evolution of understanding

Ptolemy's Universe

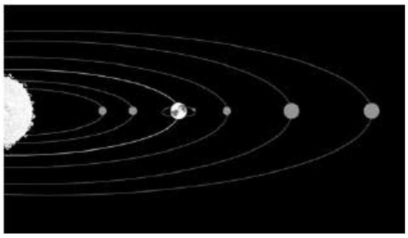


The Ptolemaic view of the Universe was an Earth-centered, or geocentric, model. The Sun and all of the planets orbited the Earth and the other stars formed a backdrop that also orbited Earth.

The Copernican Model

Sun-centered, or heliocentric, view of the Universe had been suggested by ancient Greek astronomers like Aristarchos and was later published by Polish astronomer Nicolaus Copernicus in 1543. To some extent, this model (not at actual scale in this illustration) ushered in a new age of astronomy.

The Copernican Model



The German astronomer and mathematician Johannes Kepler demonstrated that the orbits of Earth and the other planets (not drawn to scale in this illustration) were not perfectly circular but were actually elliptical, or egg-shaped.

Sun Centered Universe

- **Galileo Galilei** started observing the "heavens" with his telescope. His observations also supported the sun-centered universe model.
  - "Sun has dark patches and it rotates on an axis"
  - 4 Galiliean Moons of Jupiter
  - Phases of Venus
  - "Great cloud" – the Milky Way
  - "Saturn has ears" – the Ring of Saturn
  - The surface of moon is rough, not smooth
- His greatest contribution towards understanding our Universe is the concept of inertia.
- **Isaac Newton** first explained **WHY** Kepler's laws of planetary motion should work – the three Laws of Motion and Gravity

Sun Centered Universe - issues and problems

- The Parallax phenomena was an expected observation as the Earth orbits around the sun. However, there was no OBSERVED shift of distant stars. [well, we had to wait for Friedrich Bessel, who first precisely measured the distance of another star (*61 Cygni*) from Sun using parallax].
- With the invention of better technology (telescope) the details of Galaxy was known but even at late 20th century, SUN was still at the center of Galaxy and therefore center of the universe.
- In 1918, Harlow Shapley and Henrieta Leavitt moved the Sun from the center of the Galaxy and which was later (1923) confirmed by the observation from Hubble Telescope. In fact, it showed there are many Galaxies in the universe moving away (the Redshift).
- NOTE: Albert Einstein was already in the picture then with his special (1905) and general (1915) theory of relativity. The first one proposed that the Laws of Motion does not hold when velocities approach to that of light. The second one suggests that Newton's Law of Gravitation is only approximately correct; breaks down in at very strong gravitational fields.

… all of these and many others set the foundation of BIG BANG THEORY.

Where did we start?

The best-supported theory of our universe's origin centers on an event known as the big bang. This theory was born of the observation that other galaxies are moving away from our own at great speed in all directions, as if they had all been propelled by an ancient explosive force.

- 1927: Georges Lemaitre independently derived formulations for expanding universe.
- 1929: Edwin Hubble's observation of receding galaxies and stars supported Lemaitre's theory.
- 1931: Georges Lemaitre finally proposed the hypothesis of the primeval atom, which idealize the fact that the universe took its birth by an **explosion of primitive atom**.

Where did we start?

It happened about 13.7 billion year ego when the whole universe was concentrated in an incredibly hot and super dense point.

TIME	10^{-43} sec.	10^{-32} sec.	10^{-6} sec.	3 min.	300,000 yrs.	1 billion yrs.	9.0-9.1 billion y
TEMP	10^{32} °C	10^{27} °C	10^{13} °C	10^{8} °C	10,000 °C	-200 °C	-258 °C
	From nothing, something infinitely small dense and hot appeared. Everything that exists today was compressed into a volume smaller than the nucleus of an atom!	Post-inflation, the universe is a seething hot soup of electrons, quarks and other particles. The size is more than trillion trillion times.	Rapidly cooling universe. Gravity, electromagnetic force and the string and week nuclear interactions appear.	The nuclei of the lightest elements, H and He form.	First appearance of atom. Electrons orbit the nuclei, attracted by the protons. The universe become transparent as photons travel through space.	Galaxies acquire their definitive shape – islands of millions of star. Star explodes as supernovas and disperse heavier elements, like C.	Emergence of Solar system; "Soon after" the our Earth (the only planet known to have life).

Where did we start?

This course is certainly not meant for going in to the details of the Big Bang Theory. However, if you are interested, can click the following link and check the videos. There are also many online resources…

https://www.space.com/13352-universe-history-future-cosmos-special-report.html

Solar System Simulator

https://space.jpl.nasa.gov/

Assignment 02

- What are the evidences of the Big Bang Theory?
- Why is the Big Bang Theory unique?
- Calculate the semi-major axis of Venus using the Laws of Kepler [P=225 yrs.]
- Is the universe Expanding or Contracting? Justify.

Assignment 03

- If you are in Mars, which of the following planet(s) will show phases:

  (a) Mercury, Earth and Venus

  (b) Mercury and Venus

  (c) Venus

  (d) Saturn, Uranus and Neptune

- Illustrate a drawing to show the Sun at the centre and the orbits of Venus, Earth, and Mars. Is the figure, mark the location in Venus' orbit where a new phase of Venus can be seen from Earth. Also mark a sport with a different symbol to show where Venus will show a full phase. (use simple pencil on paper or any illustrating software (Illustrator, Corel, CAD etc.) [*clue: think the way of Galileo!]*

Summary of this lecture

- The ancients thought the Universe was geocentric
- The Renaissance: (1) Copernicus – Published evidence for heliocentricity. (2) Kepler – His elliptical planetary orbits refuted Ptolemy. (3) Galileo – Observed moons orbiting Jupiter. (4) Earth didn't center the Universe. (5) Planetary orbits weren't circular. (6) Not all bodies orbited Earth.
- The Enlightenment: (1) The Law of Universal Gravitation. (2) The Three Laws of Motion. (3) The mathematics of change (calculus).

Summary of this lecture

- The Earth is not in the center of the universe, nor the Sun.
- Earth is one of nine planets in the solar system.
- The solar system is on an arm of the Milky Way galaxy.
- Our Sun is one of 300 billion stars in this galaxy.
- The Universe contains more than a billion galaxies.

Next lecture

Origin of the Solar System

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ES0213: Fundamentals of Earth Sciences

Lecture 04. Solar System: origin and characteristics

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Origin and history of Solar System
- Chemistry and structure of young Earth

Origin of Solar System and Planets

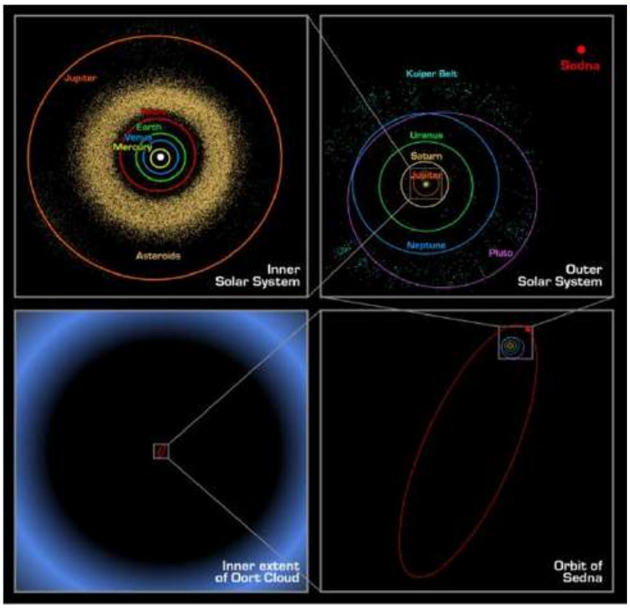
- How was the Solar System Formed?

  A viable theory for the formation of the solar system must be
  - based on physical principles (conservation of energy, momentum, the law of gravity, the law of motions, etc.),
  - able to explain all (at least most) the observable facts with reasonable accuracy, and
  - able to explain other planetary systems.

- How do we go about finding the answers?
  - **Observe:** looking for clues
  - **Guess:** come up with some explanations
  - **Test it:** see if our guess explains everything (or most of it)
  - **Try again:** if it doesn't quite work, go back to step 2.

Solar System from space

- Sun, a star, at the center…
- Inner Planets (Mercury, Venus, Earth, Mars) ~ 1 AU; They are all rocky planets…
- Asteroid Belt, ~ 3 AU
- Outer Planets (Jupiter, Saturn, Neptune, Uranus), ~ 5-40 AU; They are all gaseous planets..
- Pluto: Odd one, a comet… not a planet
- Kuiper Belt ~ 30 to 50 AU
- Oort Cloud ~ 50,000 AU; Where comets come from…



Source: NASA

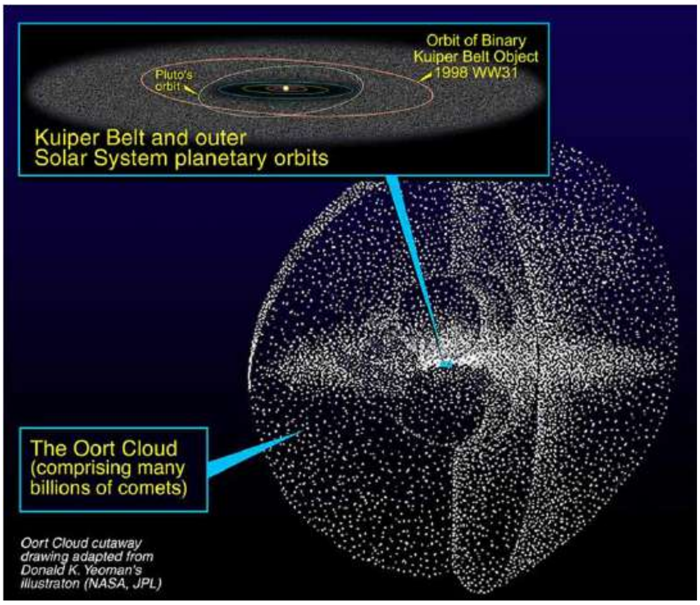
The Kuiper Belt and the Oort Cloud

- **Kuiper Belt**
  A large body of small objects orbiting (the short period comets) the Sun in a radial zone extending outward from the orbit of Neptune (30 AU) to about 50 AU. Pluto maybe the biggest of the Kuiper Belt object.

- **Oort Cloud**
  Long Period Comets (period > 200 years) seems to come mostly from a spherical region at about 50,000 AU from the Sun.

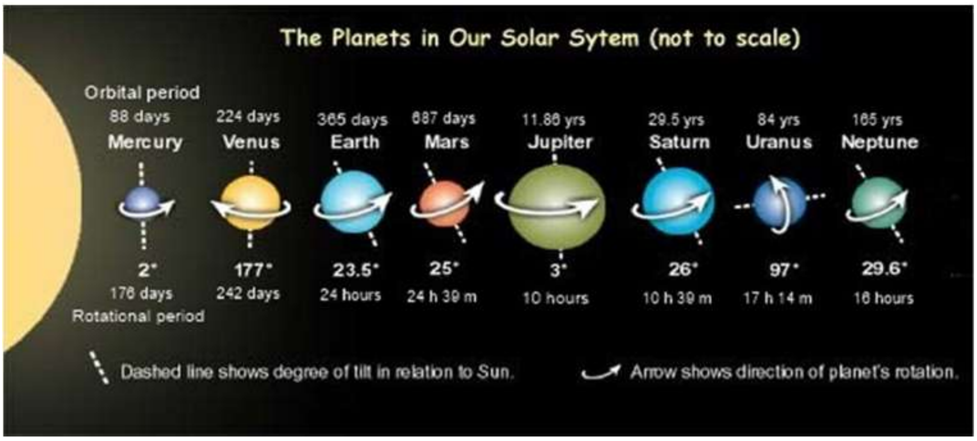
To know more on this:
http://www2.ess.ucla.edu/~jewitt/David_Jewitt.html

Source: NASA



Orbital path and spin

- All the planets orbit the Sun in the same direction
- The rotation axes of most of the planets and the Sun are roughly aligned with the rotation axes of their orbits.
- Orientation of Venus, Uranus, and Pluto's spin axes are not similar to that of the Sun and other planets.



Terrestrial and Jovian Planets

TERRESTRIAL PLANETS	JOVIAN PLANETS
Smaller size and mass	Larger size and mass
Higher density	Lower density
Made mostly of rock and metal	Made mostly H, He and other gasses
Solid Surfaces	No solid surface
Few moons and no rings	Rings and many moons
Closer to the sun and closer together with wormer surface	Further from the sun and further apart with cool temperatures

The planets

Planet	Relative Size	Dist. Frm. Sun (AU)	Avg. Equt. rads (Km)	Mass (Earth=1)	Avg. Density (g/cm³)	Orbital Period	Rotation Period	Axis Tilt	Avg. Surf. T (K)	Composition	Known Moons (2004)	Rings
Mercury		0.387	2.44	0.055	5.43	87.9 d.	58.6 d.	0.0°	700 K (D) 100K (N)	Rocks, Metals	0	No
Venus		0.723	6.051	0.82	5.24	225 d.	243 d.	177.3°	740 K	Rocks, Metals	0	No
Earth		1	6.378	1	5.52	1.00 yr.	29.93 h.	23.5°	290 K	Rocks, Metals	1	No
Mars		1.52	3.397	0.11	3.93	1.88 yr.	24.6 h.	25.5°	240 K	Rocks, Metals	2	No
Jupiter		5.2	71.492	318	1.33	11.9 yr.	9.93 h.	3.1°	125 K	H, He, Hydrogen compounds	79*	Yes
Saturn		9.54	60.268	95.2	0.7	29.4 yr.	10.6 h.	26.7°	95 K	H, He, Hydrogen compounds	31*	Yes
Uranus		19.2	25.559	14.5	1.32	83.8 yr.	17.2 h.	97.9°	60 K	H, He, Hydrogen compounds	27	Yes
Neptune		30.1	24.764	17.1	1.64	165 yr.	16.1 h.	29.6°	60 K	H, He, Hydrogen compounds	14	Yes

* Includes provisional moons

Origin of Solar System and Planets

Historically, two hypothesis were put forward to explain the formation of the solar system….

- **Gravitational Collapse of Planetary Nebula (Latin for "cloud")**

  Solar system formed form gravitational collapse of an interstellar cloud or gas.

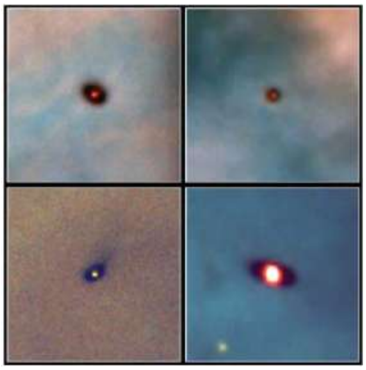
- **Close Encounter (of the Sun with another star)**

  Planets are formed from debris pulled out of the Sun during a close encounter with another star.

  But, it cannot account for the angular momentum distribution in the solar system, Probability for such encounter is small in our neighborhood…

Origin of Solar System and Planets

- Planet formation is a common outcome of star formation; but solar system is unique.
- The solar system may be unique, but to know the origin of Earth and other planets of the solar system observations of other planetary systems are necessary.
- Most developing stars, as viewed through telescopes, are approximately 99 percent gas and 1 percent dust; still they appear opaque at visible wavelengths.



Hubble images of 4 protoplanetary disks around young stars in the Orion nebula, located 1,500 light-years from the Sun. The red glow in the center of each disk is a newly formed star approximately 1 million years old.

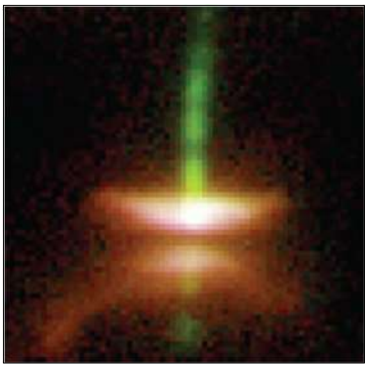


Image of Herbig-Haro 30, a prototype of a young (~1 my old) star surrounded by a thin, dark disk and emitting powerful bipolar jets of gas.. The gas jets, shown in green, are driven by accretion.

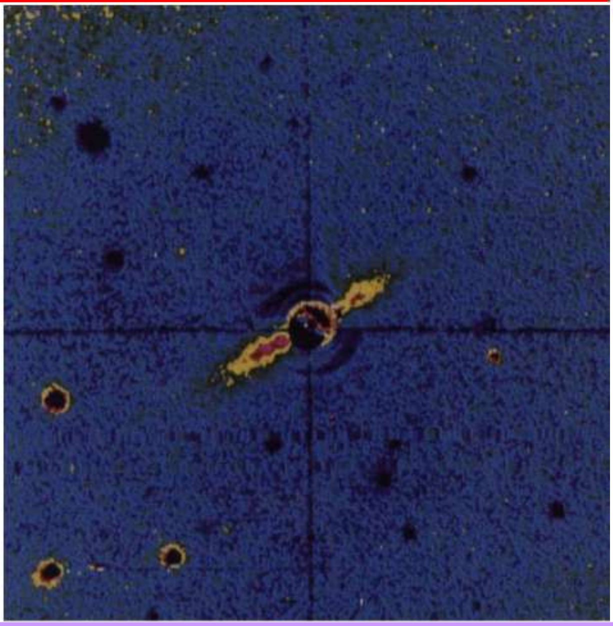
http://hubblesite.org/gallery/album/nebula_collection/

Origin of Solar System and Planets

IRAS telescope image of β Pictoris.

A solar system in the making?

Red = solid material.

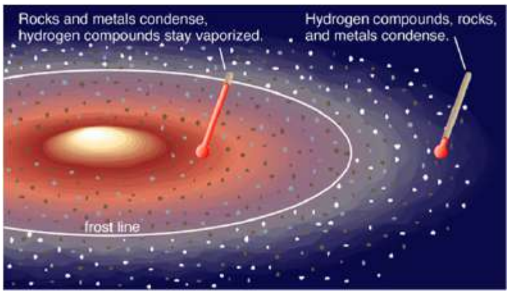


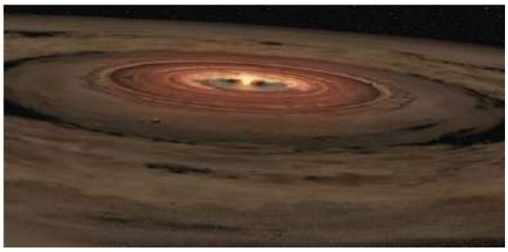
Gravitational Collapse – a scenario

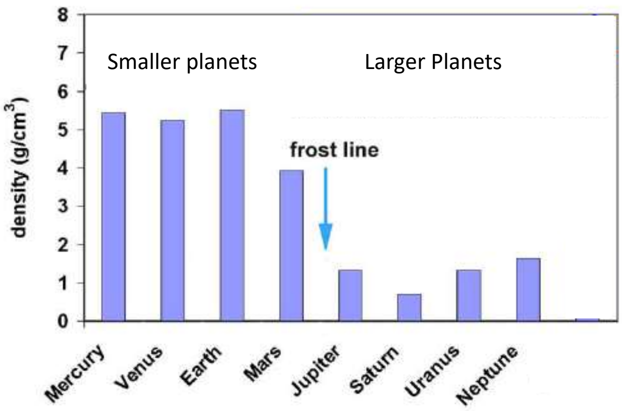
- The solar nebula was initially somewhat spherical and a few light years in diameter
  - very cold
  - rotating slightly
- It was given a "push" by some event
  - perhaps the shock wave from a nearby supernova
- As the nebula shrank, gravity increased, causing collapse
- As the nebula "falls" inward, gravitational potential energy is converted to heat.
  Conservation of Energy
- As the nebula's radius decreases, it rotates faster
  Conservation of Angular Momentum
- Finally it forms a disk like shape
  Orderly motion

Origin of Planets – Nebular Hypothesis

- In the solar system there are two major types of planets -







Origin of Planets – The model

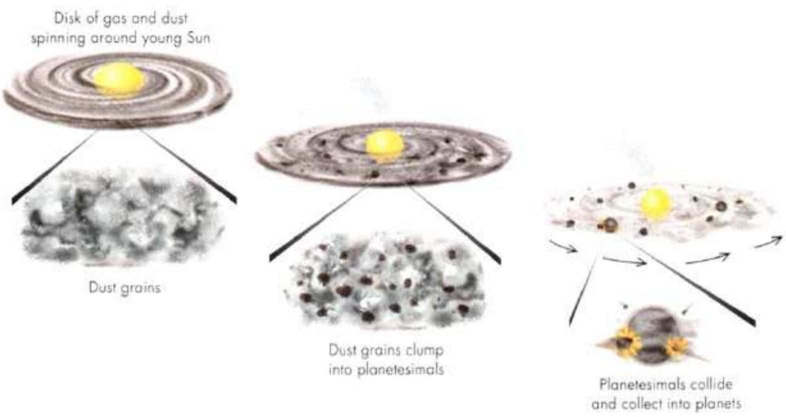
- The Nebular Hypothesis - Planeresimals

A 3rd, 4th or nth generation nebula forms 4.56 Ga.

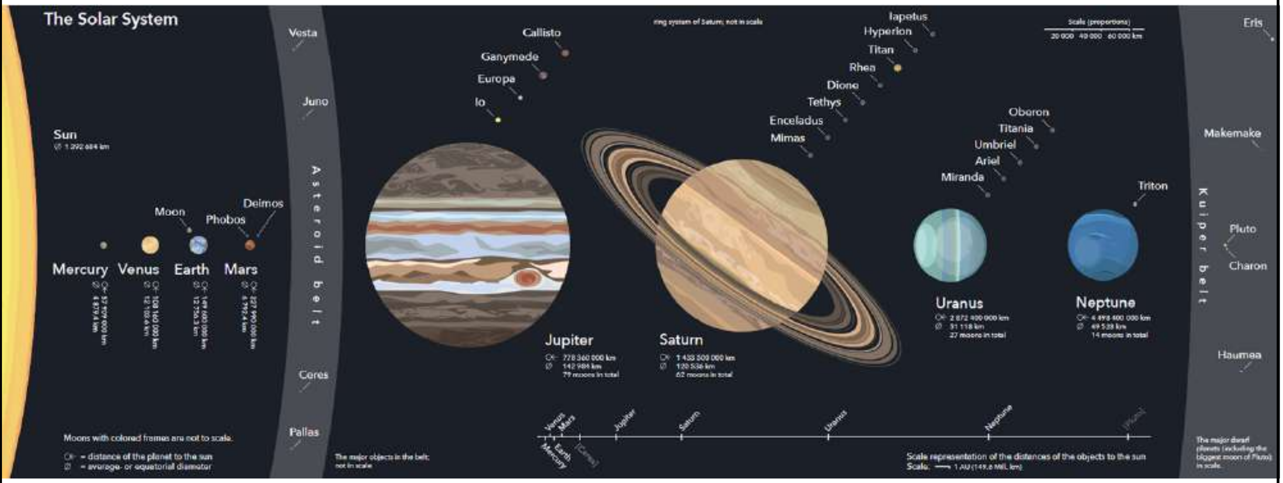
- H and He left over from the big bang.
- Heavier elements produced by stellar fusion and supernovae.

The nebula condenses into an accretion disk.

- Gravity pulls objects inward into a disk
- Causing it to spin faster and heat up.



The solar system



Origin of Planets – the solar system

- The primary difference between the inner and outer planets (rock versus gas and ice) is thought to reflect the temperature gradient in the solar nebula.

- Near the Sun, mainly silicates and metal would have condensed from the gas (so-called refractory materials), whereas beyond the asteroid belt, temperatures were low enough for ices (i.e., water, methane, ammonia) containing more volatile elements to have condensed, as well as solid silicates.

- Was the process that as the nebula cooled and solids formed unidirectional? NO. The solids typically were re-melted, re-evaporated, and re-condensed repeatedly as materials were circulated through different temperature regimes and variously affected by nebular shock waves and collisions between solid objects.

Origin of the larger planets – The models

The formation of giant planets starts with condensation and coalescence of rocky and icy material to form objects several times as massive as Earth. These solid bodies then attract and accumulate gas from the circumstellar disk (Pollack et al., 1996).

- Jupiter and Saturn, the two largest outermost planets fit well with this model as they have H and He, almost equal to solar proportions; but they have heavier elements (residing in the core) in greater than solar proportions.
- Uranus and Neptune have much less abundance of H and He compared Jupiter and Saturn; also have atmospheres consisting of solar ice.

An alternative to the standard model is that the rock and ice balls are not needed to induce the formation of gas-giant planets; they can form directly from the gas and dust in the disk, which can collapse under its own gravity like mini versions of the Sun (Boss, 2002).

Origin of the inner planets – The models

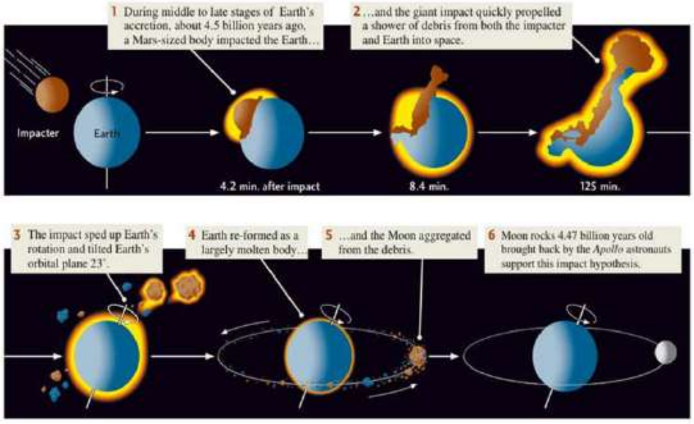
The model for the formation of inner planets is based on the information from meteorites and proposes two distinct stages of planer formation – early- and late-stage.

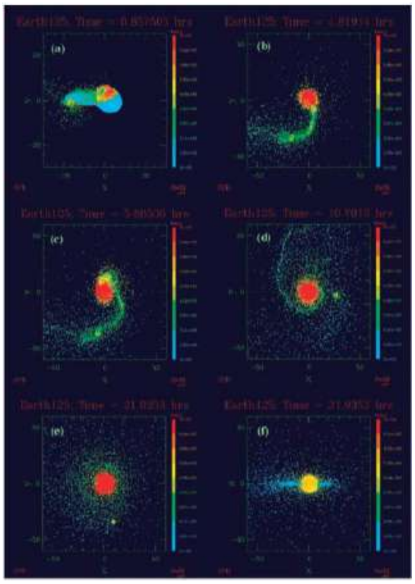
- The dust grains aggregated slowly at first, and growth accelerated along with object size as small objects were embedded into larger ones. The larger bodies are less affected by the presence of gas and their subsequent evolution is governed by mutual gravitational attractions. Gravitational interactions gave the largest planetesimals nearly circular and coplanar orbits—the most favorable conditions for sweeping up smaller objects.

- The later stages of planet formation took much longer, involved progressively fewer objects. The main phase of terrestrial planet formation probably took a few tens of millions of years. The final stages were marked by the occasional collision and merger of planetary embryos, which continued until the orbits of the resulting planets separated sufficiently to be protected from additional major collisions.

Formation of Moon - model

- Moon rocks provide one of the most persuasive pieces of evidence that Earth and the Moon have a common origin.

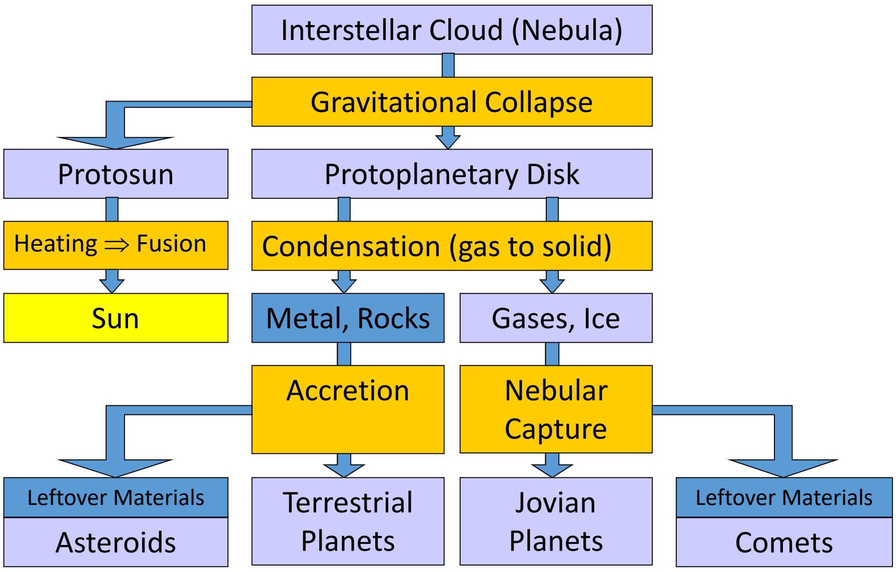




Origin of Solar System, Earth and Moon - steps

- The ball at the center grows dense and hot; fusion reactions begin – the SUN is born.
- More dust in the inner portion, more ice in the outer
    - Material accretes (clumps) into larger and larger planetesimals
    - Outer planets form ice / gas giants
    - Inner planets forms rocky, metallic planets
- Planetesimals accumulate into a larger mass
- An irregularly shaped proto-earth developed
    - Gravity shapes the earth into a sphere
    - The interior heats and becomes soft; differentiates into a Ni-Fe core and a rocky-silicate mantle and crust
- Moon formed
- The atmosphere develops from volcanic gases
- When the Earth becomes cool enough, moisture condenses and accumulates to form ocean [icy comet impact]

Origin of Solar System, Earth and Moon – Flow Diagram



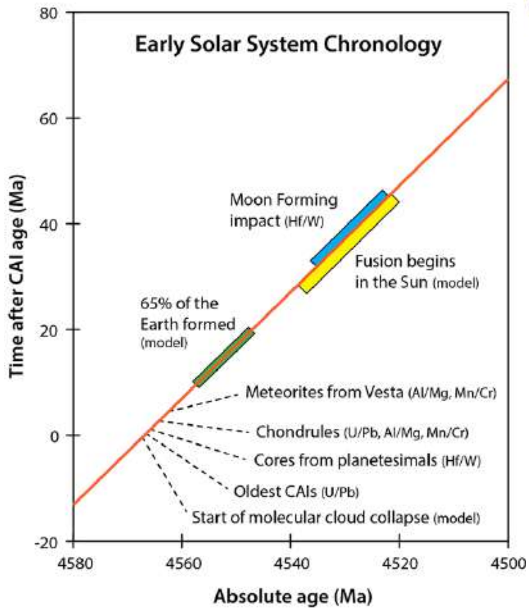
Information from meteorites

- Planets like Earth have undergone a significant geological modifications leaving hardly any evidences about the early development.
- Many meteorites, on the other hand, were not affected by the high-temperature processes that occurs in planetary interiors. Thus, they preserve significant clues about the state of the Solar System when the planets were forming.

Allende Meteorite, a carbonaceous chondrite with Ca, Al rich inclusions (CAI – irregular shaped light colour objects) and chondrules (round light colour objects).

Information from meteorites

- The most primitive chondritic meteorites contain inclusions made up of minerals that condense at high temperature from a gas of solar nebula composition. These objects, called calcium-aluminum-rich inclusions (CAI), have been precisely dated using the decay of uranium to lead, where time is measured by the accumulation of the lead decay products formed at 4,567 (±1) Ma. This age is now generally accepted as "time zero" for the Solar System.



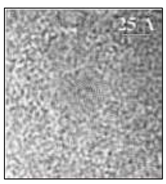
Halliday, 2006

Recent geochronological data and models for the sequence and timing of events in the early Solar System.

The primitive particles – Presolar Grains

- "Presolar grains" are stardusts manufactured by individual stars before the birth of our Solar System that are preserved in primitive meteorites.
- Each of these grains contains chemical elements that were made or reprocessed by an individual star and keeps information about the initial composition and chemical evolution.

Type	Size	Concentration in Meteorites	Sources
Diamond (C)	1-5 nanometers	1000 parts per million	Supernovae
Silicon carbide (SiC)	0.1-10 micrometers	10 parts per million	Carbon-rich giant stars, or supernovae
Graphite (C)	1-10 micrometers	2 parts per million	Supernovae and carbon-rich giant stars
Aluminum oxide (Al_2O_3)	1-5 micrometers	0.1 parts per million	oxygen-rich giant stars
Spinel ($MgAl_2O_4$)	1 micrometer	2 parts per billion	oxygen-rich giant stars
Silicon nitride (Si_3N_4)	1 micrometer	2 parts per billion	Supernovae


Nano-diamond


SiC


Graphite

Composition of primitive Earth

- At the pre-accretion stage, a very strong differentiation affected by the solar wind, light pressure, short-lived temperature rise, and magnetic separation – GAS COMPONENTS MOSTLY REMOVED.
- The young Earth was a relatively cold celestial body. Nowhere within it had temperature exceeded the melting point of the Earth matter.
- The primordial Earth had a relatively uniform composition. Therefore, there was no Earth core at that time, and there was no chemical stratification into the mantle and crust.
- The source matter was hydro-silicates, carbonates, and sulfur as well as bases and some other easily fusible elements.

Composition of primitive Earth

Oxides	Comp. of conti. Crust [a]	Comp. of Mantle [b]	Comp. of Core	Comp. of Primordial matter (calculated)	Avg. Comp. of chondrites [c]	Avg. Comp. of coaly chondrites [d]
SiO_2	59.3	45.400	–	30.710	38.040	33.000
TiO_2	0.7	0.600	–	0.410	0.110	0.110
Al_2O_3	15.0	3.700	–	2.540	2.500	2.530
Fe_2O_3	2.4	1.970	–	–	–	–
FeO	5.6	6.550	49.340	22.760	12.450	22.000
MnO	0.1	0.130	–	0.090	0.250	0.240
MgO	1.9	38.400	–	25.810	23.840	23.000
CaO	7.2	2.300	–	1.570	1.950	2.320
Na_2O	2.5	0.430	–	0.300	0.950	0.720
K_2O	2.1	0.012	–	0.016	0.170	–
Cr_2O_3	–	0.410	–	0.280	0.360	0.490
P_2O_5	0.2	–	–	–	–	0.380
NiO	–	0.100	–	0.070	–	–
FeS	–	–	6.690	2.170	5.760	13.600
Fe	–	–	43.410	13.100	11.760	–
NiO	–	–	0.560	0.180	1.340	–
Total	100.0	100.000	100.000	100.000	99.480	98.390

[a] Ronov and Yaroshevsky (1978).

[b] Dmitriyev (1973) and Ringwood (1966).

[c] Urey and Craig (1953).

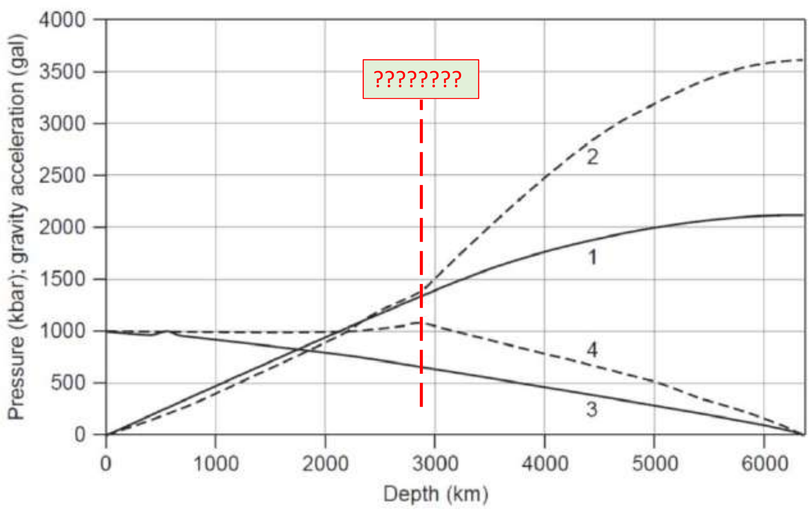
[d] *"Outlines of comparative planetology."* Nauka (1981)

Structure of primitive Earth

Depth (km)	Density (g/cm³)	Temperature (K)	Pressure (kbar)	g (cm/s²)
0	3.92	260	0	985
200	4.15	1147	82	980
400	4.38	1385	168	973
400	4.5	1385	168	973
600	4.76	1457	261	986
670	4.85	1294	285	955
670	5.02	1294	285	955
800	5.16	1433	358	941
1000	5.36	1411	456	921
1200	5.53	1400	556	898
1400	5.68	1393	656	874
1600	5.81	1387	754	848
1800	5.93	1384	852	821
2000	6.04	1381	1381	793

Depth (km)	Density (g/cm³)	Temperature (K)	Pressure (kbar)	g (cm/s²)
2200	6.15	1379	1042	764
2400	6.25	1378	1133	734
2600	6.35	1377	1223	703
2800	6.44	1376	1309	670
3000	6.52	1375	1393	638
3400	6.66	1373	1548	569
3800	6.78	1371	1688	498
4200	6.9	1369	1810	425
2600	6.99	1367	1912	350
5000	7.07	1365	1995	273
5400	7.11	1363	2057	196
5800	7.15	1361	2097	119
6200	7.18	1359	2116	52
6360	7.18	1358	2116	0

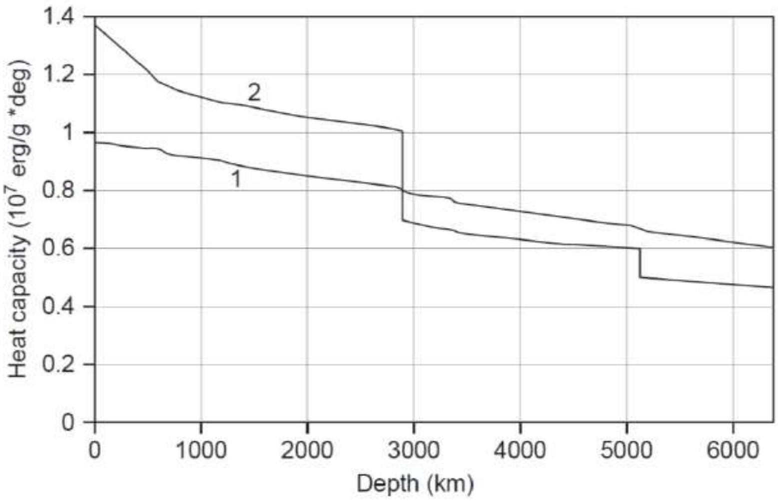
Pressure and Gravity Distribution



Pressure distribution
1: young Earth;
2: present-day Earth;

Gravity acceleration
3: young Earth;
4: present-day Earth.

Heat Capacity Distribution



Hear Capacity
1: young Earth;
2: present-day Earth;

Suggested Reading

- The origin and Evolution of the Solar System – MM Woolfson 2000, IoP

Next Lecture

We shall talk about the Earth as a System and learn some of its basic principles

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ES0213A: Fundamentals of Earth Sciences

Lecture 05. Earth as a System

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Experimental Rock Deformation Laboratory

Aims of this lecture

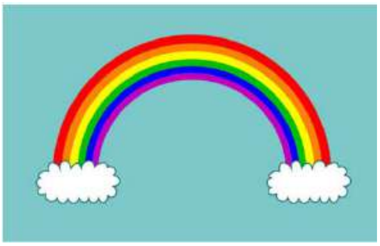
- Earth as a SYSTEM
- Definition and components of Earth (and Planetary) system

The Blue Planet

- Few basic and exclusive features
  - WATER – in liquid form on the surface
  - PLATE TECTONICS – active
  - ATMOSPHERE – O_2 rich and filters solar radiation
  - MAGNETIC FIELD – relatively strong
  - **LIFE** – primitive to intelligent

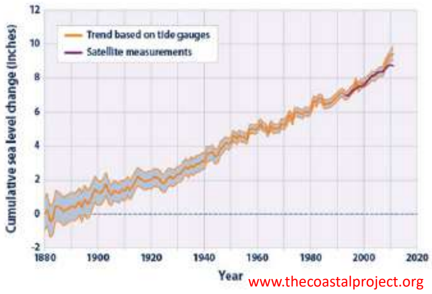
Do we know?

- **A Rainbow changes the sky brightness**
  - 1. True
  - 2. False

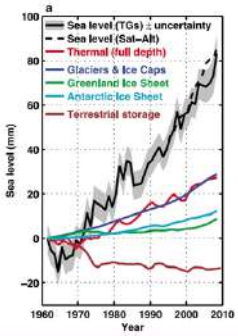


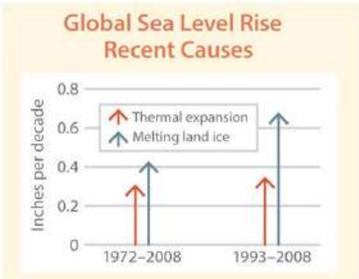
Do we know?

- **The main reason of present day sea-level rise**
  - 1. Melting of glaciers and ice-sheets
  - 2. More rain-fall
  - 3. Warming of ocean and sea water
  - 4. Ground water discharge to oceans



www.thecoastalproject.org

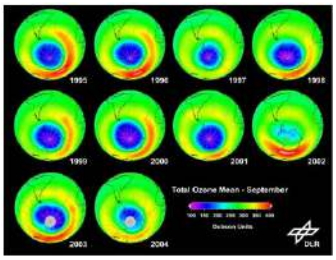




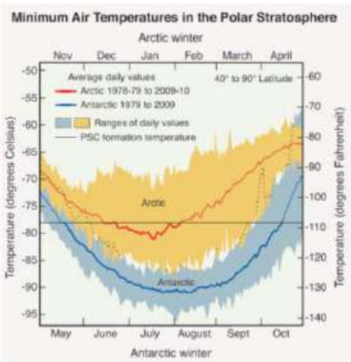
Church & White 2001;
Cazenave and Llovel, 2010

Do we know?

- **The hole / thinning in the ozone layer is related to GLOBAL WARMING.**
  - 1. Agree
  - 2. Disagree



- … and why we have the hole primarily over the Antarctic region?



Chlorofluorocarbons (CFCs) and other halogenated ozone depleting substances (ODS) are mainly responsible for man-made chemical ozone depletion.

The southern polar region is colder and more isolated than the north. Lower temperatures favor the formation of polar stratospheric clouds (PSCs) which serve as platforms for catalytic ozone breakdown. Unlike the Arctic, the circulation over the Antarctic is more persistent and vortex-like as a consequence of having less land. Air inside the vortex is prevented from mixing with warmer, ozone-rich air from lower latitudes. This vortex is not a feature of the Arctic. IOW, the chemistry of ozone loss works in both poles, but their meteorological conditions are different.

Do we know?

- **The maximum contribution of oxygen in the atmosphere comes from**
  - 1. Terrestrial biosphere
  - 2. Marine biosphere
  - 3. Volcanic eruption
  - 4. Washing powder !

The main source (~80%) of atmospheric oxygen, on Earth, is cyanobacteria (aka "blue-green algae") in the ocean.

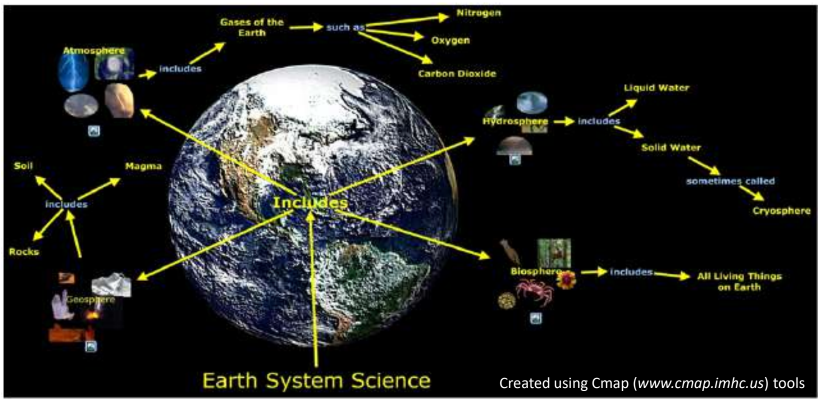
[Source: NASA]

System

- SYSTEM: A system is a group of related objects or parts or components that work together to form a whole.
- COMPLEX SYSTEM: Many of the individual components are themselves systems (subsystems).
- NONLINEAR SYSTEM: A particular issue cannot be judged by simply adding the effects of independent components, because there are hardly any independent components.

System – Earth System

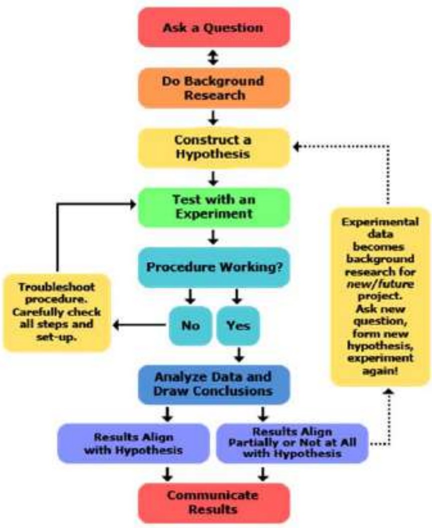
- EARTH: The densest planet in the Solar System and the only astronomical object known to have Oxygen rich atmosphere and accommodate life.
- EARTH SYSTEM: A system that considers and manages all of the matter, energy, and processes within Earth's boundary. The system is very much complex made of living and nonliving things, and matter and energy continuously cycle, interact and evolve through the smaller systems.



+ ANTHROPOSPHERE ?

Earth System Processes – a study of science?

- The Scientific Methods –What most of us follow

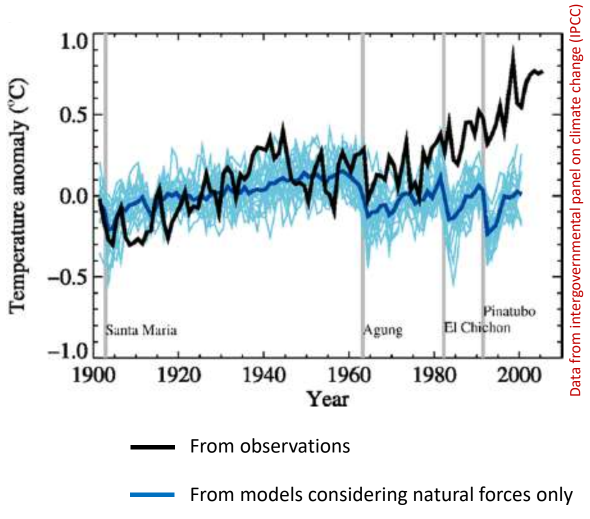


- HYPOTHESIS: an explanation based on guess, untested
- THEORY: an idea that has passed through many experiments and observations with few unexplained issues.
- LAW / PRINCIPLE: – a full proof theory; no exceptions.

Earth System Processes – a study of science?

- OBSERVATION: the average temperature of Earth is increasing over the last century.
- HYPOTHESIS: More volcanic activity, increasing solar radiation variability (i.e., natural changes – that happened even before) are responsible for the increasing temperature
- TEST: The hypothesis worked well until 1978-80. But an anomaly after that time! The hypothesis failed to explain.

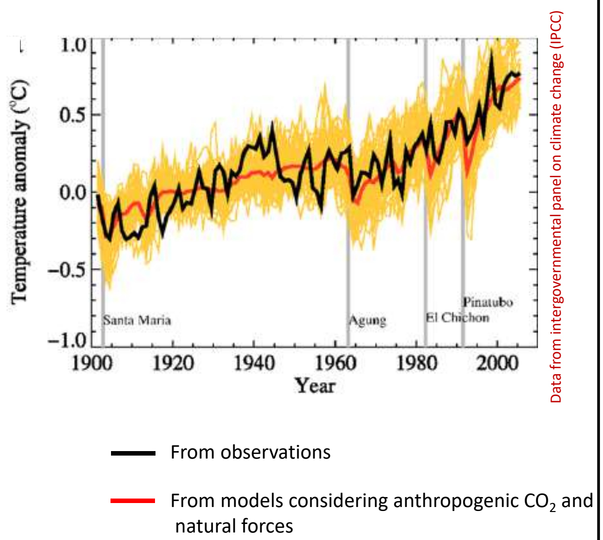
.. Reject the hypothesis and think for a new one.



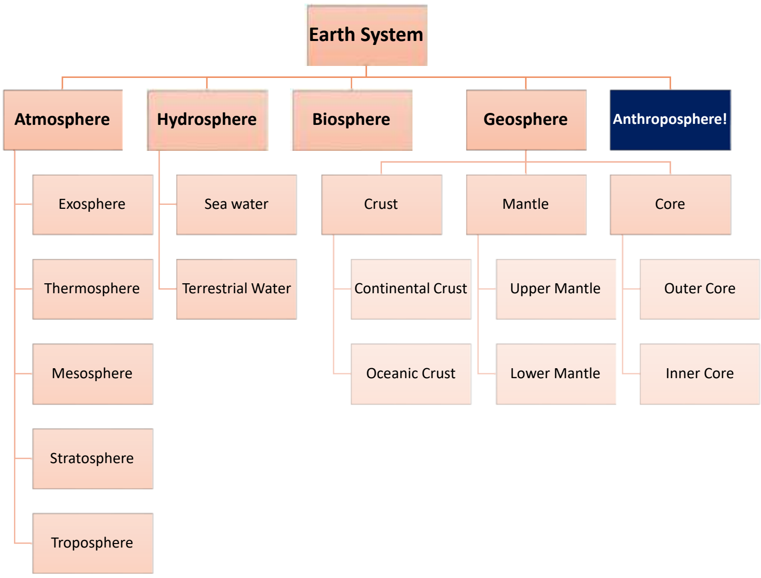
Earth System Processes – a study of science?

- OBSERVATION: the average temperature of Earth is increasing over the last century.
- HYPOTHESIS: Anthropogenic activities (more CO_2, methane and land-use) together with natural changes are the reason for global temperature increase.
- TEST: The hypothesis worked perfect and showed an excellent correlation.

.. However, after the successful test results, it remains still a hypothesis; not a theory or law as there are many local anomalies and level of uncertainty.



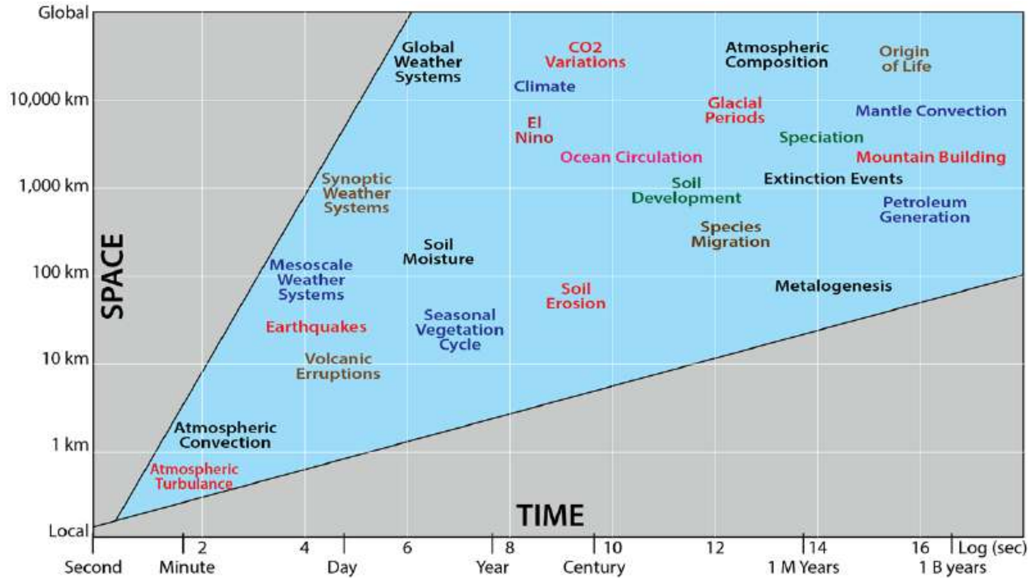
Hierarchy of Earth System – the components



The mutual interactions – Earth as a System

- OPEN systems defined as those that exchange energy (heat) and mass with other systems; CLOSED system only exchange energy. [more on this in the next lecture]
- The forces that drive heat and mass transfer include chemical potential, temperature and pressure gradients, Causing diffusion, reaction and advection (flow) – mostly irreversible with time.
- MODELS are developed considering time-dependency, degree of linearity, deterministic and / or probabilistic to simulate the earth as a system.
- Primary importance -
  - Different kinds of subsystems (e.g. the atmosphere, hydrosphere etc.)
  - Components of the subsystem (air, water, rocks, minerals etc.)
  - Physico-chemical state of the components (Pressure, temperature, composition etc.)
  - Interactions and mechanisms between sub-systems (fluxes of matter and energy)

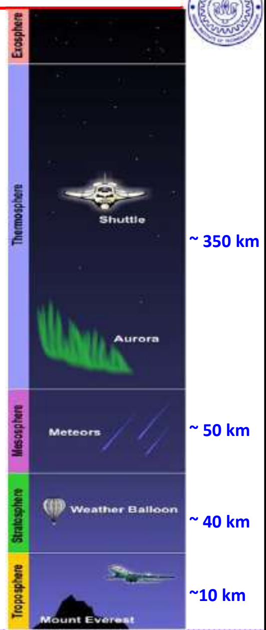
Spatial-Temporal and Geological-Environmental events



Source: NASA, 1986

The Atmosphere

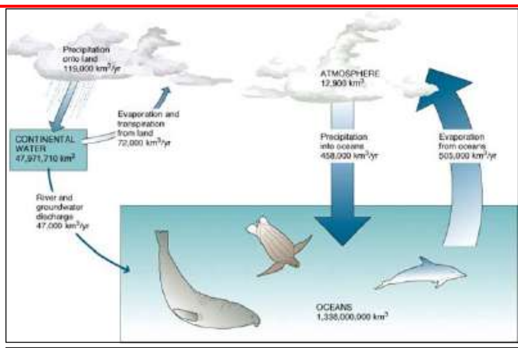
- The earth's atmosphere is a very thin layer wrapped around a very large planet
- Two gases make up the bulk of the earth's atmosphere: nitrogen (78% of the atmosphere), and oxygen (21%). Various trace gases make up the remainder.
- Based on temperature, the atmosphere is divided into four layers: the **troposphere**, **stratosphere**, **mesosphere**, and **thermosphere**. The outermost layer is exosphere.
- Energy is transferred between the earth's surface and the atmosphere via conduction, convection, and radiation.
- Ocean currents (and winds, too) play a significant role in transferring this heat poleward. Major currents, such as the northward flowing Gulf Stream, transport tremendous amounts of heat poleward and contribute to the development of many types of weather phenomena.

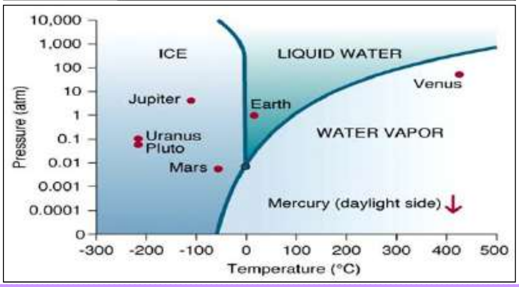


We shall spend a week in the atmosphere…

Hydrosphere

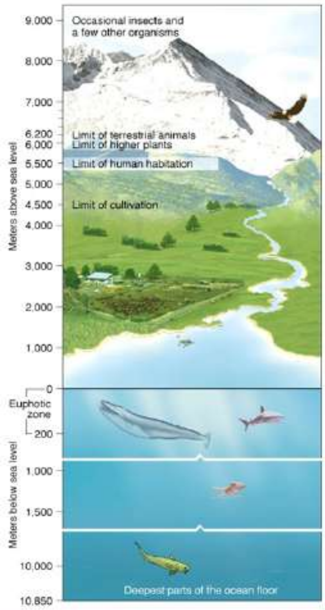
- Earth- the only watery planet! The BLUE planet.
- All forms of H_2O: water, ice, water-vapour.
- Responsible for many of the landform and surface features on continents.
- Without surface water, there would be no rivers, valleys, glaciers etc.





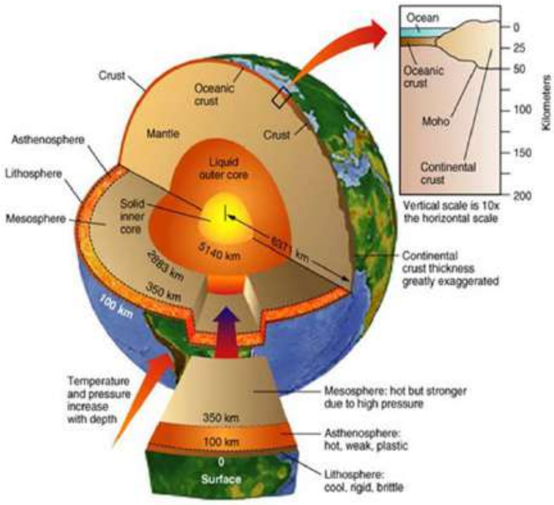
The Biosphere

- Considers the living world - microbes, plants, and animals. Age- 3.5 billion years.
- The biosphere extends to any place that life of any kind might exist. The biosphere extends to the upper areas of the atmosphere where birds and insects can be found. It also reaches to dark caves deep in the ground or to the bottom of the ocean at hydrothermal vents.
- Factors, that control the existence and diversity of the Biosphere
  - Big factors: distance from sun, tilt of earth, seasonal variation
  - Small factors: climate, daily weather, erosion, earthquake
  - Micro-factors: chemical erosion, oxidation, reduction.
  - What about US! Are we also a factor to biosphere?



The Geosphere

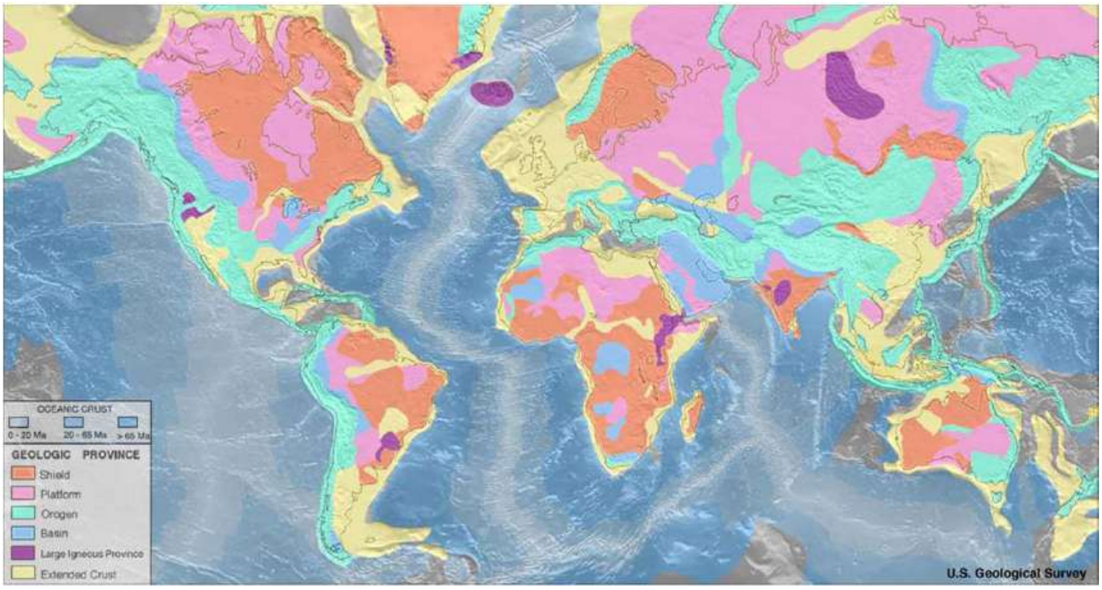
- While the whole Earth (crust, mantle and core) plays the role, the PEDOSPHERE and LITHOSPHERE have a greater participation is earth system.
- **Continental crust** – 35-65 km; Varied rock types, rich in Si and Al (lighter); Relatively Old (4.6 billion years).
- **Oceanic crust** - ~5 km; Volcanic rocks, rich in Mg and Fe (dense), Relative young (<150 my).
- **Lithosphere** – rigid (brittle), rocky outer layer of the Earth, consisting of the crust and the solid outermost layer of the upper mantle (~100 km). It is segmented as plates.
- **Asthenosphere** – layer beneath the lithosphere, covers the mantle from ~100-350 km and is much hotter and more fluid (ductile) than the lithosphere.
- **LAB** – Lithosphere-Asthenosphere Boundary.



The Geosphere – Continental Crust & Lithosphere

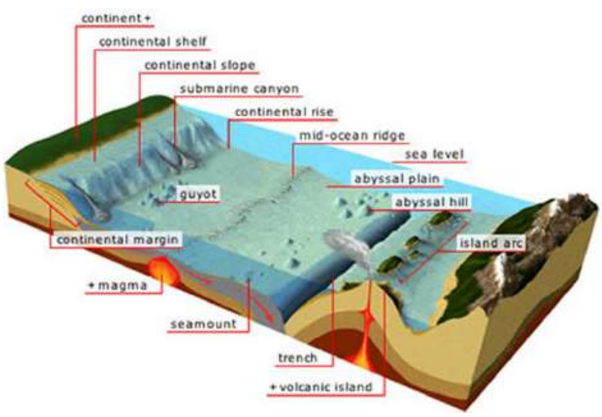
- Shields: deeply eroded expanses of low relief, which have been stable since Precambrian times.
- Platforms: similar to the above, but mantled by thick sedimentary cover, which may be entirely or in part Phanerozoic in age.
- Orogens: long, curved belts of folded rocks, usually forming mountain chains, mostly formed by continental collisions.
- Rifts: linear, fault-bounded depressions, traversing continents; these are the structures which originate crustal splitting and dispersion, and lead to midocean ridge formation, but they may, as in the case of the East African Rifts, be aborted, i.e., never developed into oceans.

The Geosphere – Continental Crust & Lithosphere

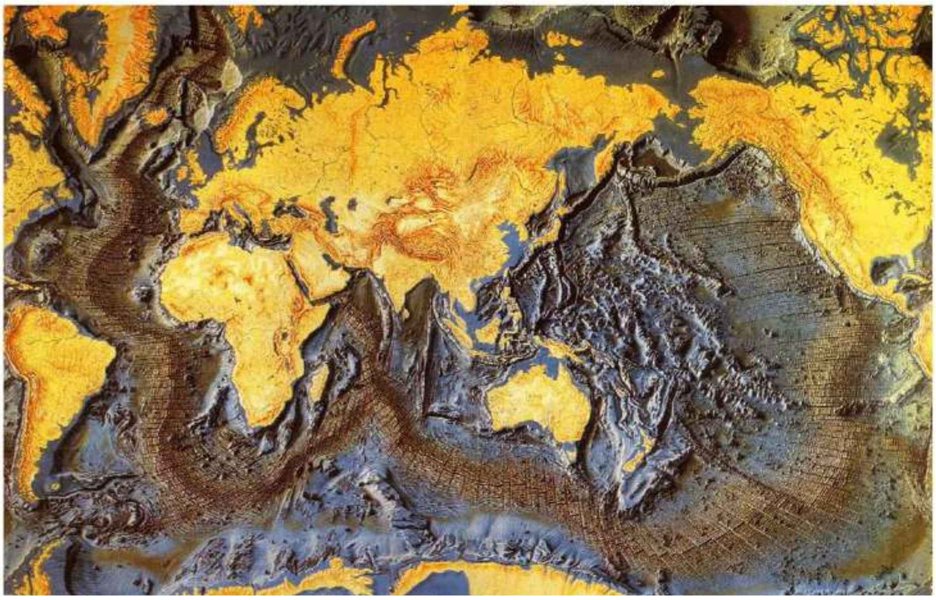


The Geosphere – Oceanic Crust & Lithosphere

- Volcanic islands: scatterings or chains of islands which mark mantle hotspots.
- Volcanic / Island arcs: above subduction zones (e.g., Aleutian Islands), these may be represented by their eroded underworks – chains of calc-alkaline batholiths (e.g., Peru).
- Trenches: the outer margin of subduction zones; the deepest parts of the oceans.
- Ocean basins/abyssal plains: the extensive flat, deep areas of oceans, beyond continental slopes.
- Marginal basins: small basins separating arcs, or landward from arcs (back-arc basins).
- Inland seas: seas within continents (e.g., Caspian).
- Mid Oceanic Ridge: underwater mountain range, typically having a valley known as a rift running along its axis, formed by plate tectonics. This type of oceanic ridge is characteristic of what is known as an oceanic spreading center

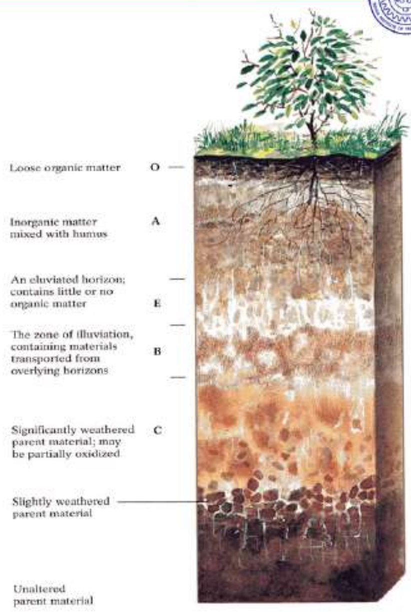


Continental and Oceanic Crusts: surface morphology



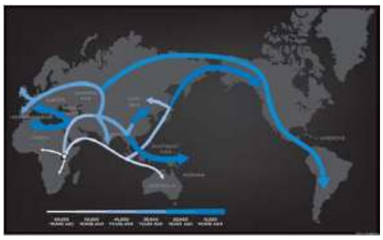
The Pedosphere

- Soils – disaggregated and weathered rock debris and organic matter.
- 100-200 m thick, supports all terrestrial agricultural activities and food production.
- Open system; rate of soil formation depends upon climate, rock type, organic matter, topography and time.
- Factors, that control soil formation
    - Parent material / rock
    - Topography
    - Animal and plant activity
    - Climate (rainfall, temperature)
    - Time



Anthroposphere

- 50-100 k years : Homo Sapiens appeared in Africa and migration started
- 25-12 k years : Ice age conditions; new land appeared, helped in migration
- 10 k years : Warmer global climate ; agriculture developed; domesticated animals; diversion of streams, irrigation canals, dams
- 7 k years : First cities arose; use of metals, fuels
- 1700 k years : Industrial revolution



Accelerated growth in the last few hundred years – exponential growth

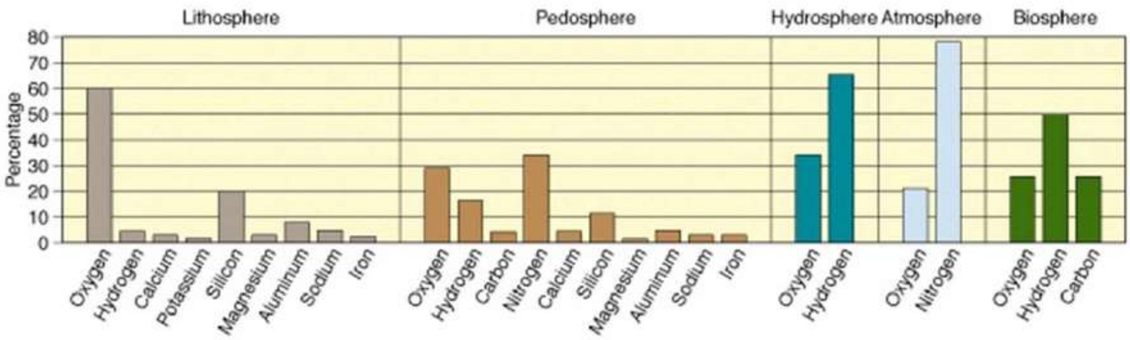
Post 1700 scenario

- Human population expanded
- Competition for food, air, water and space
- Negative impacts
  - Air/water pollution
  - Soil erosion
  - Concentration of waste
  - Diseases

Last few centuries

What else can you think?

Composition of Earth System



Suggested Additional Reading

- Summerfield, S.A. (1991) Global Geomorphology, Longman.
- Ernst, W.G. (2000) Earth Systems: Processes and Issues, Cambridge University Press.
- Merrits, D., Dewet, A. and Menking, K. (1998) Environmental Geology: An earth system science approach. W.H. Freeman.

Next Lecture

Principles of the Earth

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ES0213A: Fundamentals of Earth Sciences

Lecture 06. Principles of the Earth

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Experimental Rock Deformation Laboratory

IITK

Aims of this lecture

- Earth Systems – is it a closed or open system
- Positive and negative feedbacks in Earth Sciences
- Cycles of different elements of the Earth

System: Open Vs. Closes

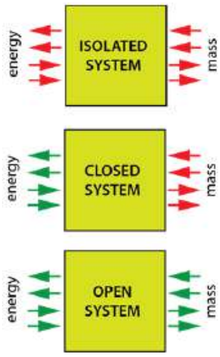
- We have learnt: A system is a group of related objects or parts or components that work together to form a whole. The boundary of the "whole" defines the limit of the system.

  The system is classified and characterized by if it exchanges mass and/or energy across its boundary.

- ISOLATED system: A system that does not allow the exchange of either mass and/or energy with its surroundings.

- CLOSED system: A system that does not allow the exchange of mass, but energy (mostly in the form of heat) with its surroundings.

- OPEN system: A system that allows the exchange of both mass and energy with its surroundings.



The mutual interactions – Earth as a System

- The EARTH SYSTEM -
  - is an open system.
  - is a closed system.
  - is both open and closed system.

- Are we losing and / or gaining something (material/mass)?
  - IN: meteorites, asteroids, comets
  - OUT: hydrogen, helium

- Implications of living inside a near closed system….
  - Everything (e.g., resources) are finite and limited
  - Change in one component affect others
  - Cannot "dump" or throw-away anything

Are you aware of something called "asteroid mining"

The general approach to study Earth as a System

- Identification of the components and their mutual interactions
- Determination of the rate of mutual interactions - the RESIDENCE TIME
- Identification of the FEEDBACK loops – amplification (positive) and / or attenuation (negative) of the features

FEW BASIC TERMS

Reservoir: amount of material of interest in a given time

Flux: amount of material added to (*the source*), or removed from (*the sink*) reservoir, in a given period of time

Steady state: no net change in amount of materials [source =sink]

Resident time: the time requires to empty / fill the reservoir

$$Resedinet\ time = \frac{capacity\ of\ the\ reservoir}{total\ source\ or\ total\ sink}$$

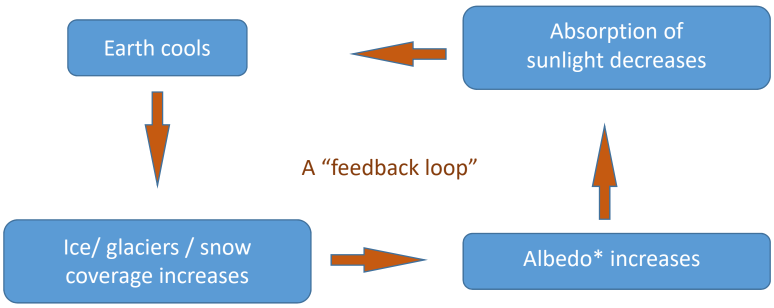
Feedbacks

- **Positive (+) feedbacks** amplify a disturbance and add more to the original sate.
- **Negative (-) feedbacks** return components of a system towards their original state after a small perturbation – act like a stabilizers and eliminates the stimulus.

Remember please: The feedback loops have nothing to do with GOOD (+) or BAD (-)

Feedbacks

- The Earth System, in general, is governed by either positive or negative feedback loops…

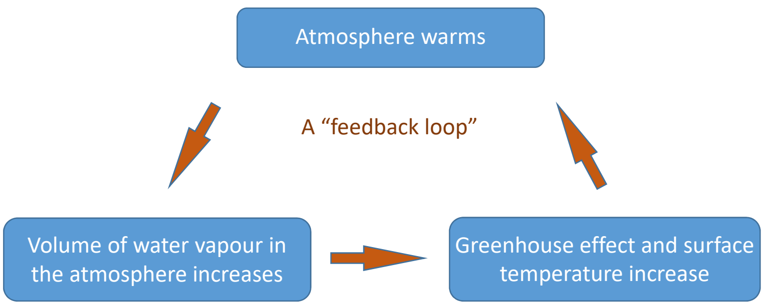


Positive or negative feedback loop?

***Albedo** is a measure of how much light that hits a surface is reflected without being absorbed.

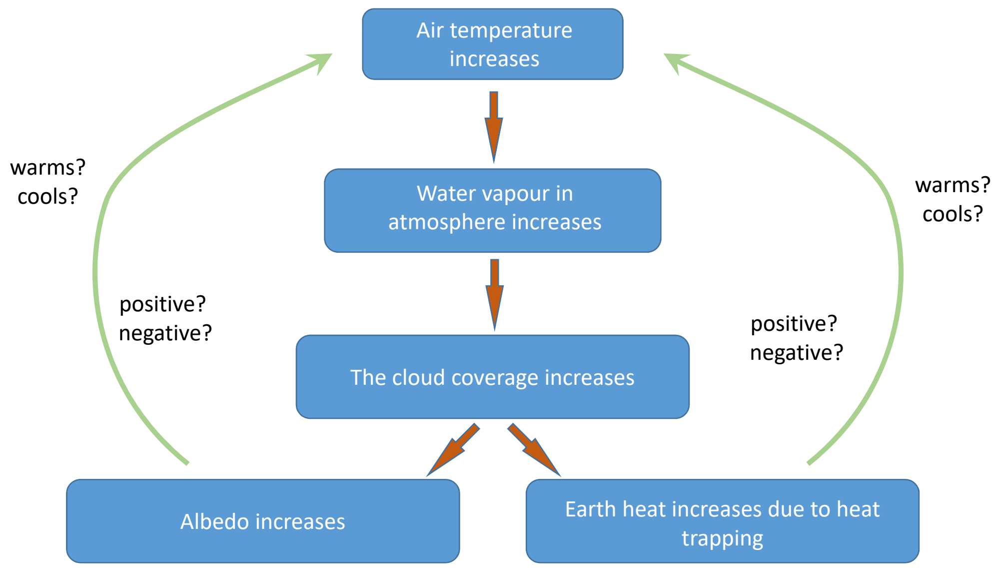
Feedbacks

- The Earth System, in general, is governed by either positive or negative feedback loops…



Positive or negative feedback loop?

Feedbacks – more examples



Chaos

- The feedback loops and the mutual interactions are so complicated that the best explanation / prediction is provided by **CHAOS THEORY** – a science of surprises, extreme nonlinearity and unpredictability.

  - Butterfly effect (sensitivity): some complex dynamical systems exhibit unpredictable behaviors such that small variances in the initial conditions could have profound and widely divergent effects on the system's outcomes.
  - Fractal Geometry (Self-similarity): An object looks the same at any scale. Many natural objects approximate fractal geometry, such as clouds, snowflakes, river drainage systems, and coastlines.
  - Self-organized criticality (SOC): A dynamic system will move toward a critical or emergent, state, by natural processes.

Fractal Geometry and Natural Power Law

- The relationship between the size of an earthquake and its frequency of occurrence follows fractal statistics. Very large earthquakes are rare (M>8 - 9) and very small earthquakes (M<2-4) are very frequent.

Magnitude	Last week	Last month	Last year
< 2	132	635	7384
2 - 3	168	776	10267
3 - 4	17	95	1527
4 - 5	6	57	547
5 - 6	0	4	75
>= 6	0	0	4
Total	323	1567	19804

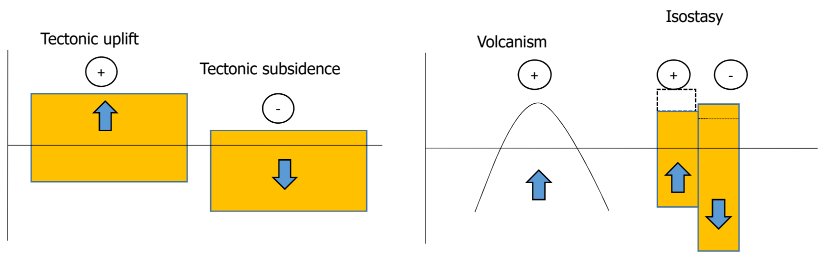
Earthquake Data, New Zealand (Geonet)

- There is a power law relationship between how many large and how many small earthquakes there must be in a given region per unit time. For instance, every year and globally, there is on average just one earthquake of magnitude eight, ten magnitude seven, one hundred magnitude six, one thousand magnitude five, and so on.

More on this in the Earthquake lecture

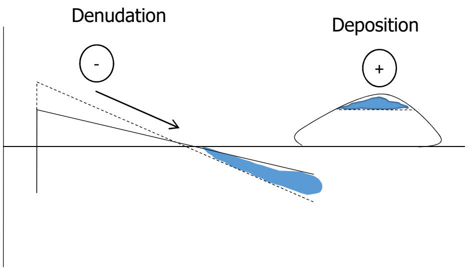
Some key concepts - ENDOGENIC processes

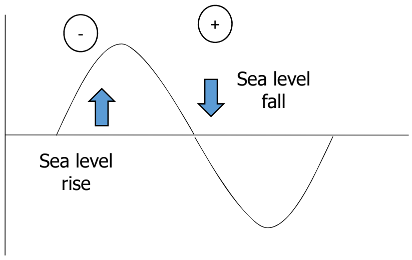
- **Endogenic Processes –** An action/object coming from within a system. The process originates in the earth's interior and are governed by the forces inherent in the earth and affected little by external influences.



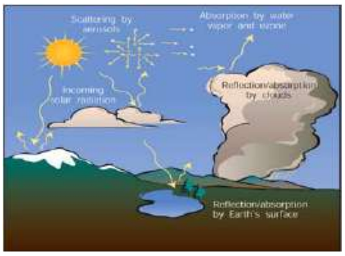
Some key concepts - EXOGENIC processes

- **Exogenic Processes –** an action/object coming from outside a system. The processes derive their energy from sources external in relation to the earth – i) solar radiation, ii) wind-action; iii) impacts by extra-terrestrial objects etc.

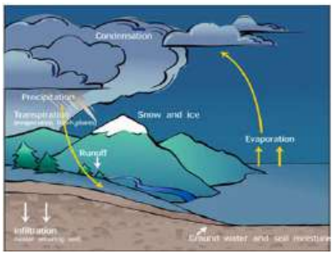




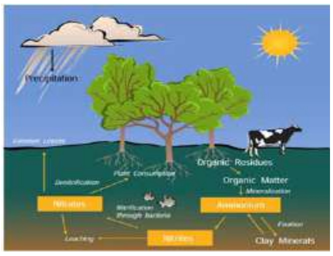
Earth's various cycles



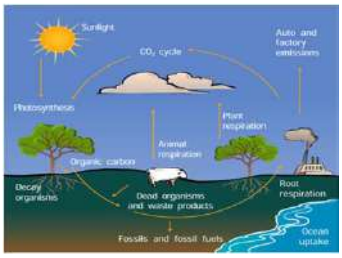
- Energy Cycle



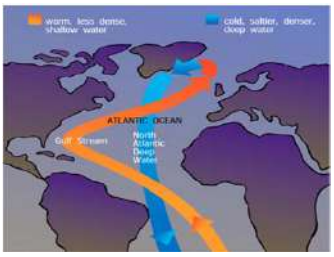
- Water Cycle



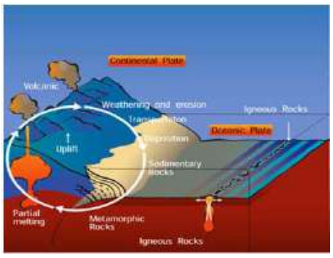
- Nitrogen Cycle



- Carbon Cycle



- Ocean Cycle



- Rock Cycle

Next Lecture

Energy in Earth: Sources and Distributions

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ES0213A: Fundamentals of Earth Sciences

Lecture 07. Earth's Energy

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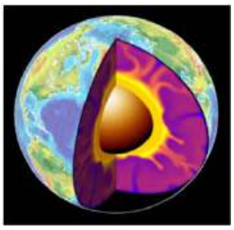
Experimental Rock Deformation Laboratory

Aims of this lecture

- Earth's resources of energy
- Atmospheric effect on Energy radiation
- Greenhouse effect
- Earth's Energy balance

Global energy Sources



Internal Heat

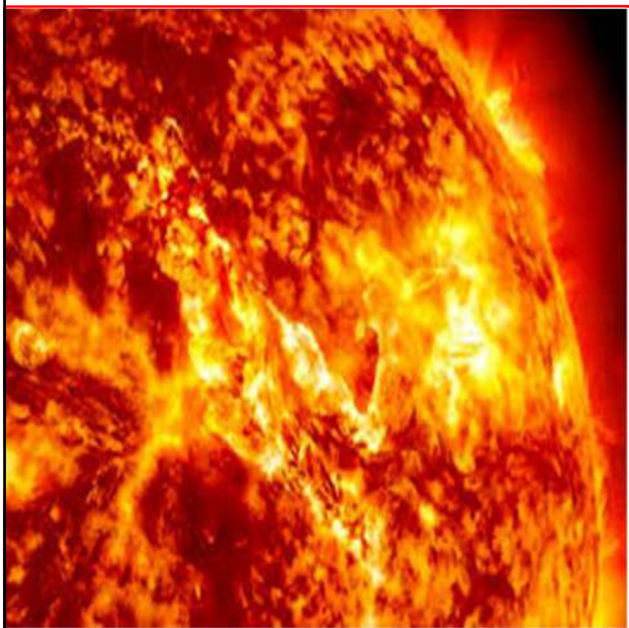
- Earth's matter gravity differentiation by density. It results in Earth's stratification into the high-density iron-oxide core, the residual silicate mantle, the light aluminosilicate crust, and the hydrosphere with the atmosphere.
- Decay of radioactive elements causing the release of heat energy

We will have a dedicated class on this…

External Heat

- From Sun
- From impact

SUN – our star, the furnace



- The sun is a furnace that produces heat energy when H nuclei undergo fusion to He.
- The sun consists of unburned H and He residue
- Sun is considered to be a BLACK BODY as it absorbs all light shined upon it and it emits a spectrum of light (a function of temperature).
- Luminosity (power output): 3.865 x 10^{26} Watts. Since its birth, it has lost about 30% of its luminosity.
- It still has a life about 3-4 billion years from now, till its H reservoir runs out

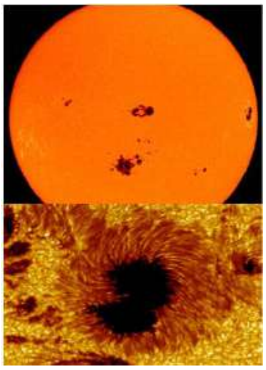
SUN – our star, the furnace

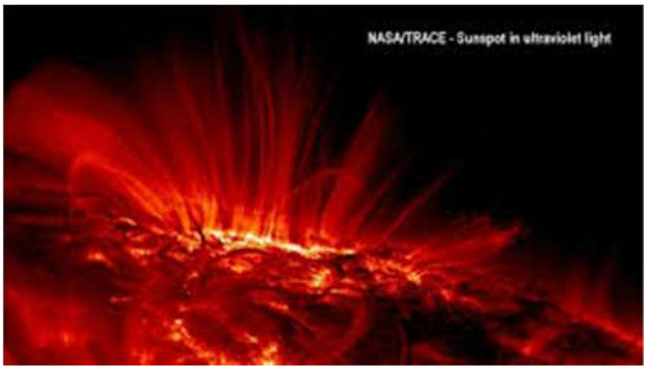
- In context to our Earth's energy, the SUN delivers two "products" we are concern about -

PLASMA RADIATION

PLASMA

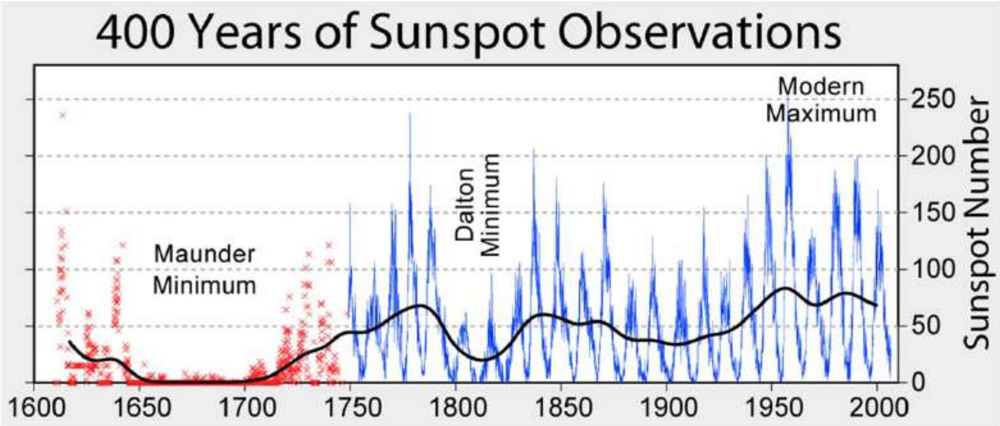
- In the Sun's core, T = 15.6 million K and the pressure is 300 billions times that of Earth's. T on sun's surface is 6000 K
- These extreme conditions break the Sun's H and He atoms into a swirling mass of charged particles - PLASMA
- These plasma particles are always in motion due to sun's strong magnetic field. A burst of such magnetism produces a SUNSPOT. Cooler than average ~ 4500 K.





PLASMA

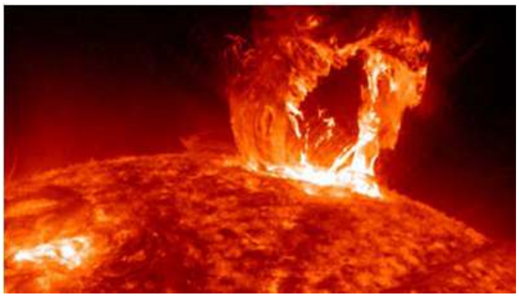
- On short term, sunspots on 11 year cycle cause a small change in global temperature (~ 0.1 K change)



Remember, butterfly effect !

PLASMA

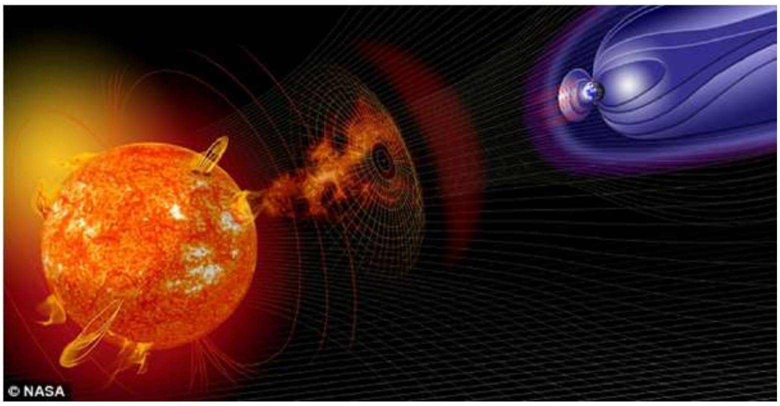
- A sufficiently strong magnetic irregularity may cause plasma to arc off the sun's surface as a SOLAR FLARE.
- The solar flare can also leave the Sun's strong gravitational field as CORONAL MASS EJECTION (CME).



- Eventually the CMEs hit earth. Why aren't we roasted, baked and boiled?

PLASMA

- It is our own magnetic field (the protective magnetic shield) that saves us… and 1) produces auroras (borealis and australis), which forms when particles enter earths atmosphere near the poles.



- Field Electronics – satellite communications, electrical outages (Quebec 1989).

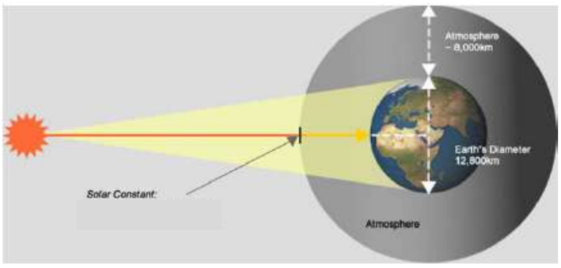
PLASMA

- How much time it requires for CMEs (velocity ~ 3 million km/hr) to reach earth?

$$time_{CME} = (\text{distance from Sun/ CME velocity}) = 50 \text{ hours}$$

- How much energy (solar constant, $\mathbf{S_o}$) we receive from sun?

  [solar constant, $\mathbf{S_o}$ = Luminosity / Area of the coverage sphere]



Radiation

- The sun continuously emits radiant energy, aka RADIATION
- What is radiation?
  - Transfer of energy that occurs when energized waves travel
  - Does it require a medium? In vacuum?
  - What is the speed of radiation? Constant or variable?
  - Who / what can emit radiation?

Radiation

- **Stefan-Boltzmann Law - I**: Warmer objects emit radiation more intensely than coo objects do.

$$E = \sigma T^4$$

E : Radiation in Watts/m^2
σ : Stefan-Boltsmann constant = 5.67 x 10^{-8} Wm^{-2} K^{-4}
T : Temperature (in Kelvin)

- **Wien's law**: Warmer objects emit shorter wavelengths; cooler objects emits larger wavelengths

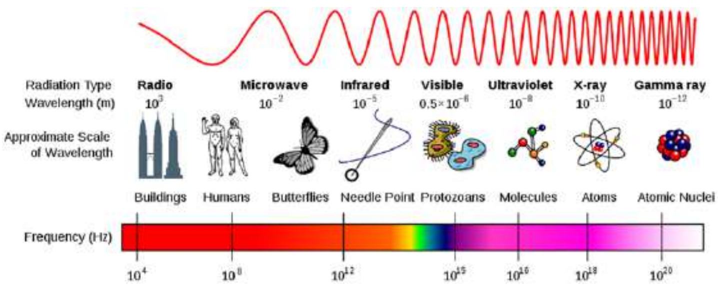
$$\lambda_{max} = \frac{C}{T}$$

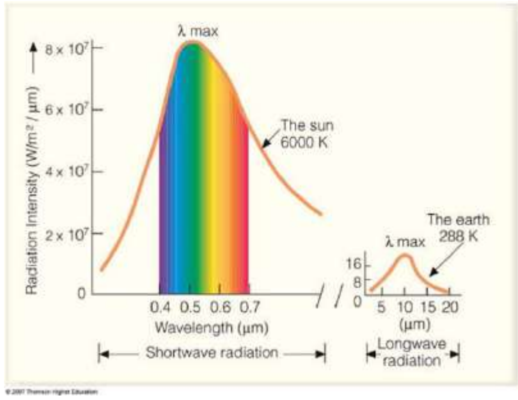
L : wavelength (μm)
C : constant = 3000 μm K
T : Temperature (in Kelvin)

Warmer objects: Large intensity and shorter wavelengths
Cooler objects: Less intensity and higher wavelengths

Radiation

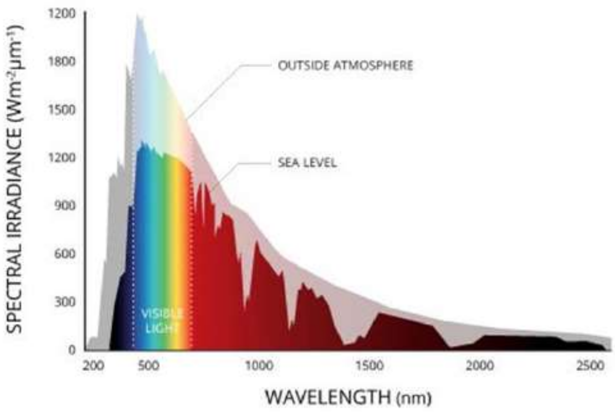
- λ_{max} *(SUN) = 0.5 μm*
- λ_{max} *(EARTH) = ~10 μm*





Radiation from Sun and Earth

- **INSOLATION** - **Incoming Solar Radiation:** Intensity of incoming solar radiation on an object (Flux / Unit Area)



Heat Balance

- **Stefan-Boltzmann law - II**: Each planet must balance net incoming solar radiation with outgoing radiation, determined by its temperature.

$$(1 - \alpha)\, \pi R^2 S_o \quad = \quad 4\pi R^2 \sigma T^4$$

α	: Earth's albedo (30%)
R	:Radius of Earth (6371 km)
S_0	: Solar Constant for Earth (1367 Wm^{-2})
σ	: Sterfan-Boltzman Constant (5.67 x 10^{-8} Wm^{-2} K^{-4})
T	: Temperature in Kelvin

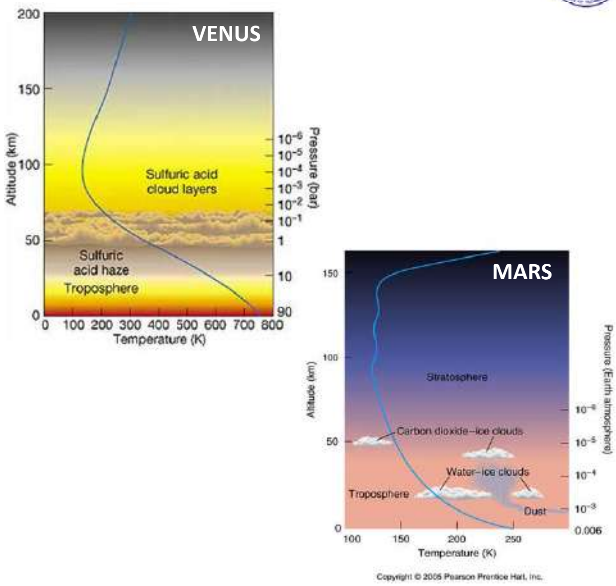
Temperatures of inner planets




	Albedo (α)	Equilibrium T (°C)	Actual surface T (°C)
Mercury	0.1	162	180
		Just about agrees	
Venus	0.59	-10	453
		Disagrees badly	
Earth	0.31	-18	15
		Disagrees	
Mars	0.15	-55	-43
		Nearly agrees	

Temperatures of inner planets

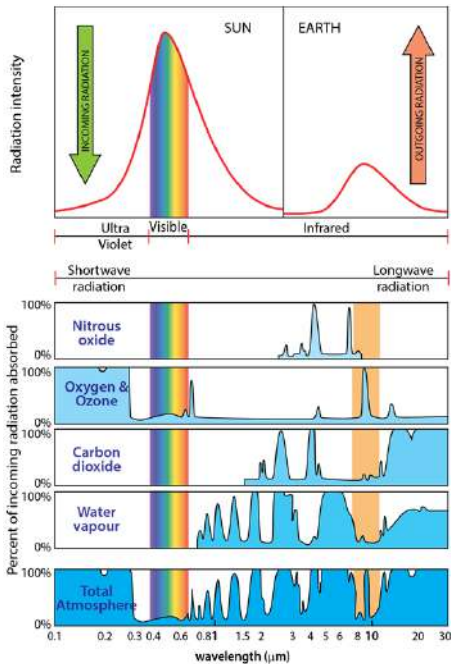
- Radiative equilibrium works well for Mercury (no atmosphere) and just about for Mars (thin atmosphere).. But not for Earth and Venus.
- The disagreement for Venus and the Earth is because these two planets have atmospheres containing certain gases which modify their surface temperatures.
- This is the 'Greenhouse Effect' in action:
  - Earth's surface is 34°C warmer than if there were no atmosphere
  - Venus has a 'runaway' Greenhouse effect, and is over 400°C warmer
  - Mars atmosphere slightly warms its surface, by about 10°C
- The existence of the Greenhouse Effect is universally accepted (it is not controversial), and it links the composition of a planet's atmosphere to its surface temperature.



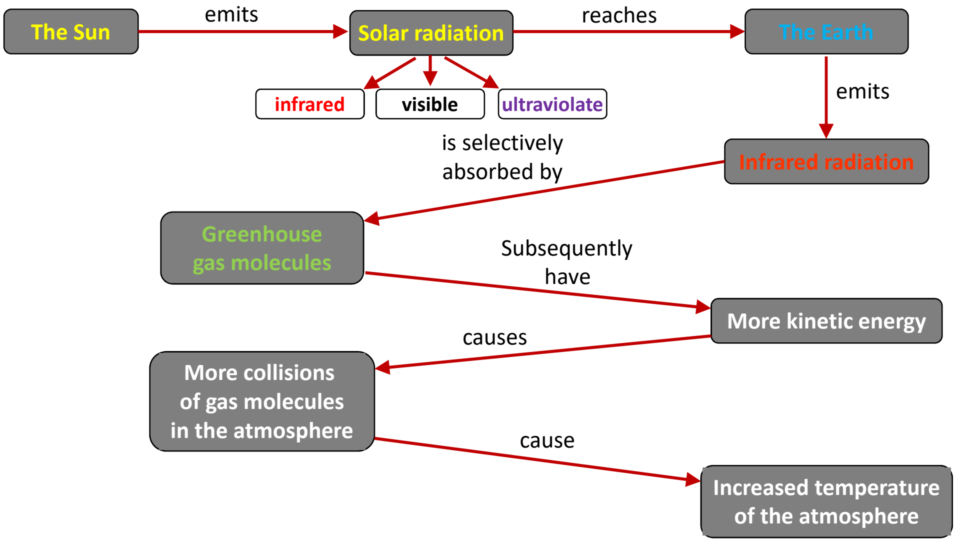
The greenhouse effect

- Sun's peak output is visible light
- Earth's Atmosphere transmits visible light (radiation). This radiation reaches the surface, absorbed and warms the surface (Insolation).
- Earth's surface is, however, much colder than that of the sun. Earth's peak output is longer wavelength infrared radiation.
- The greenhouse gases in the atmosphere absorb infrared and warm the atmosphere.

Is GREENHOUSE EFFECT good or bad for us?

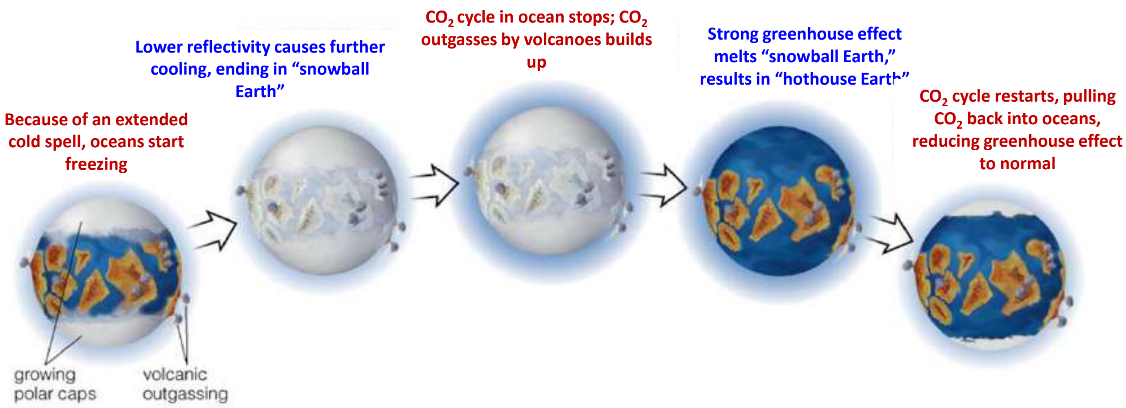


The greenhouse effect – flow chart



The snowball Earth

- We know that a cold earth makes a colder Earth (remember positive feedback loop!)
- We also know that there were few ice-ages, when the surface of the Earth was covered by snow and ice. The last one happened about 635 million years ago. Oceans froze to a depth of 1 km and stayed about 12 million years.
- How did the Earth manage to melt all the ice and snow to make itself again habitable?



Global warming – a quick poll

- Is global warming real?
  - Yes
  - No
- How much has the average temperature of the Earth risen in the last 100 years?
  - ~ 0.5°C
  - ~ 5.0°C
  - ~ 10.0°C
  - ~ 1.0°C
- This is the highest temperature ever recorded in Earth's history.
  - Yes
  - No
- Who is responsible for Global Warming?
  - Human Activities
  - Natural causes
  - ET
  - Hard to tell
- Which gas in the atmosphere is to blame?
  - Ozone
  - CO_2
  - H_2O
  - O_2

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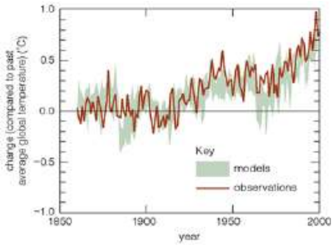
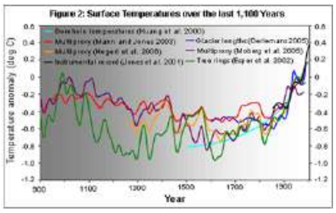
Global warming – the scenario



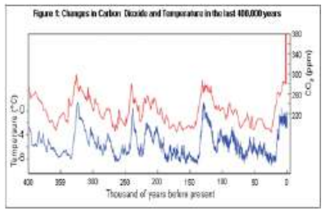
There is a gradual increase in the average temperature of the Earth's atmosphere in the last 100 years…It has risen about 1°C since 1900…

- *Are human activities causing global warming?*
- *What other (non-human) factors can cause global warming?*
- *How does global warming affect our life?*



Reconstructions of surface temperature variations from six research teams. Each curve illustrates a somewhat different history of temperature changes, with a range of uncertainties that tend to increase backward in time (as indicated by the shading).

NRC, 2006. National Academy of Sciences, Courtesy of the National Academies Press. Washington, D.C.



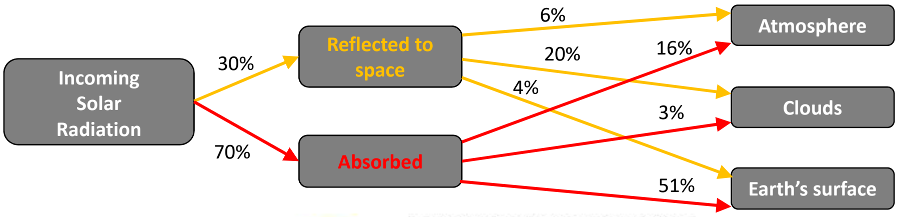
Fluctuations in temperature (blue) and in the atmospheric concentration of carbon dioxide (red) over the past 400,000 years as inferred from Antarctic ice-core records. The vertical red bar is the increase in atmospheric carbon dioxide levels over the past two centuries and before 2006.

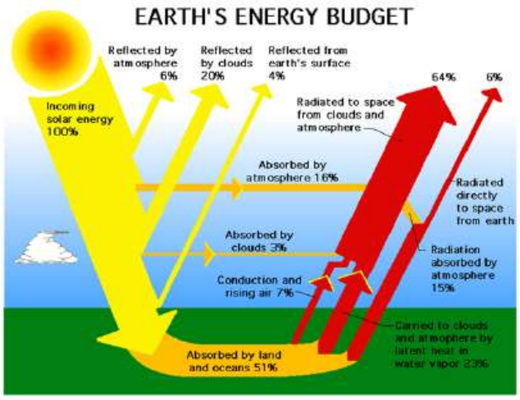
A. V. Fedorov et al. *Science* 312, 1485 (2006).

What's the big deal if CO_2 causes 1°C temperature increase?

- An increase in atmospheric temperature (human or natural origin) will lead to the increase in the water vapor content of the **troposphere.**
- Because water vapor is a strong greenhouse gas, the increase in H_2O vapor in turn causes enhanced greenhouse effect, raising the temperature more.
- Higher atmospheric temperature will cause more evaporation of water
- Which leads to even higher temperature… POSITIVE FEEDBACK LOOP… and effectively culminate to Runaway Greenhouse Effect.

Earth’s Energy Balance



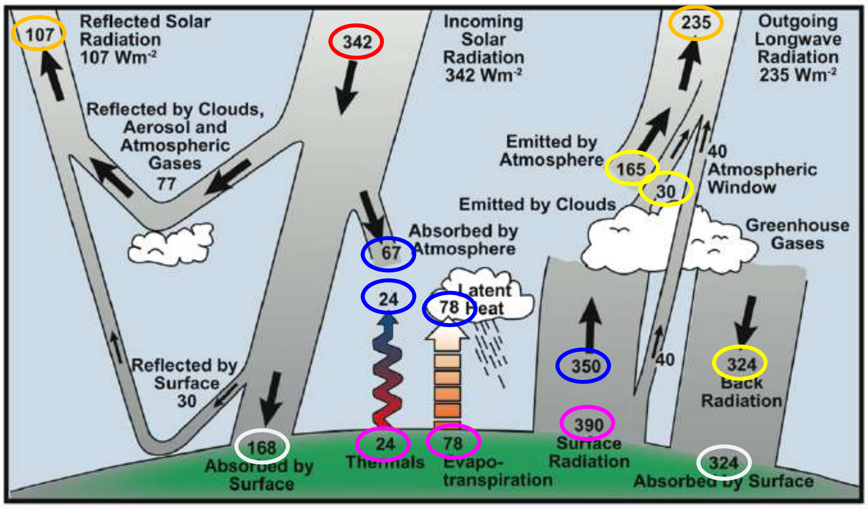


Earth’s Energy Balance

342 Energy entering top of atmosphere = Energy leaving top of atmosphere 107+235

67+350+78+24 Energy gained by atmosphere = Energy lost by atmosphere 165+324+30

168+324 Energy entering Earth’s surface = Energy leaving Earth’s surface 24+78+390



Next Lecture

Concept of Plate Tectonics

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ES0213A: Fundamentals of Earth Sciences

Lecture 08. Concept of Plate Tectonics - I

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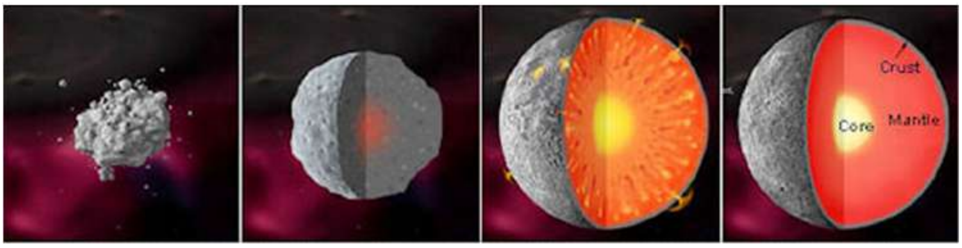
Experimental Rock Deformation Laboratory

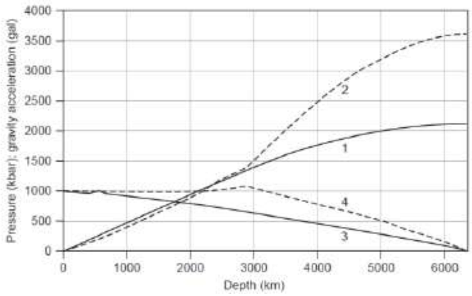
Aims of this lecture

- Origin of the Theory – Continental Drift
- Evidences and Problems

Reference: Chapter 3, Marshak's Book

Layered structure of the Earth



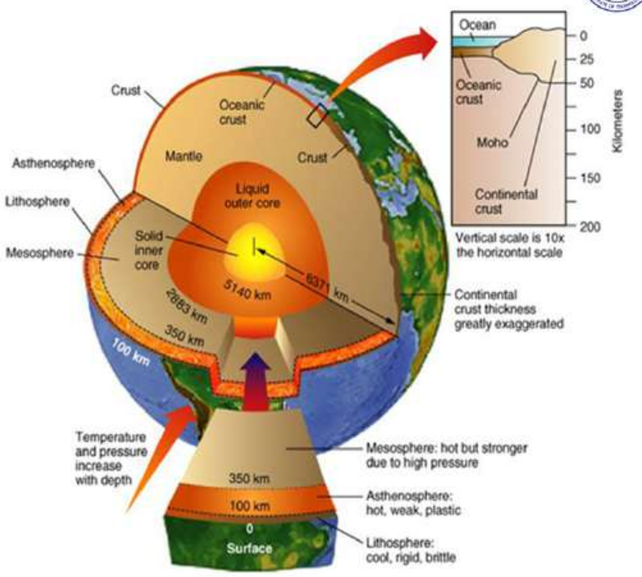


Pressure distribution
1: young Earth;
2: present-day Earth;

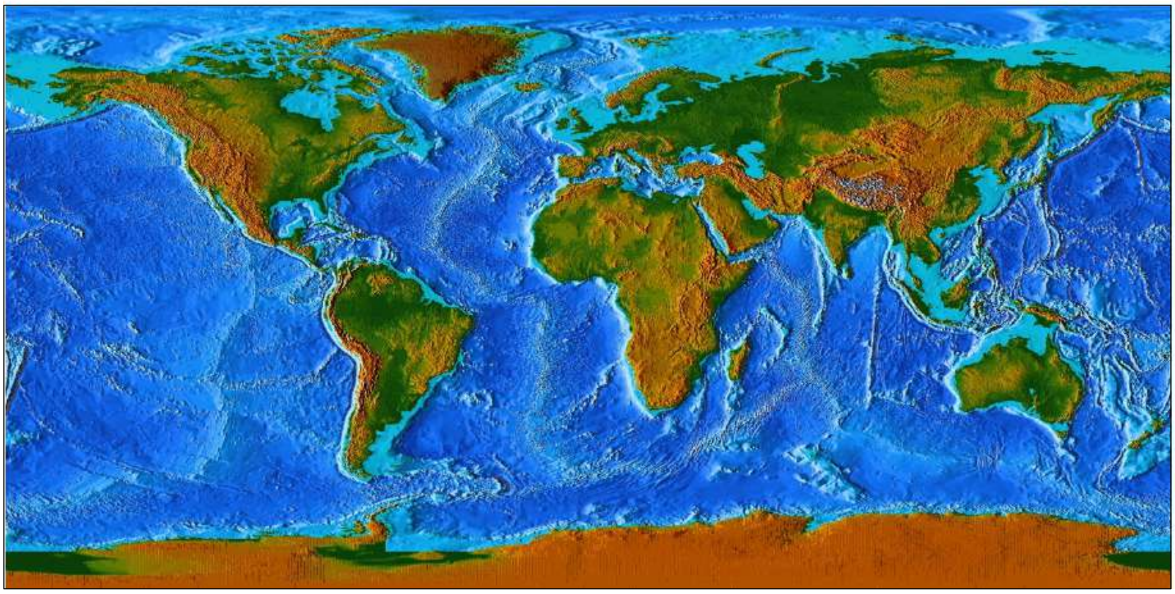
Gravity acceleration
3: young Earth;
4: present-day Earth.

Layered structure of the Earth

- **Compositional Layers**
  - Crust (Si, Al, Ca)
  - Mantle (Mg, Fe, Si, Al, Ca)
  - Core (Fe, Ni)
- **Mechanical Layers (Strength & Rheology)**
  - Lithosphere (Brittle)
  - Asthenosphere (Ductile & Viscous)
  - Mesosphere (Viscous, but extremely strong)



The surface of the Earth



The surface of the Earth

WHY??

… are the continents where they are?

… are the oceans where they are?

… are the mountain ranges where they are?

… do we have earthquakes and volcanoes?

Historical developments

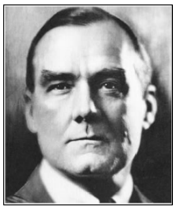
Abraham Ortelius (1527-1598), a Dutch cartographer suggested:

Americas were "*torn away from Europe and Africa … by earthquakes and floods*" and went on to say: "*The vestiges of the rupture reveal themselves, if someone brings forward a map of the world and considers carefully the coasts of the three continents* …..

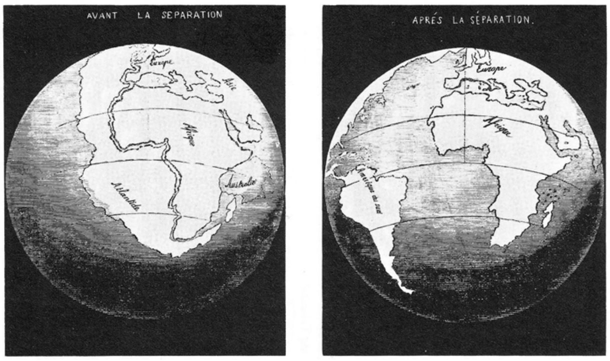
[*Thesaurus Geographicus, 1556*]

Historical developments

Antonio Snider-Pellegrini (1802–1885), a French geographer and scientist prepared two maps of the world.



In 1858, Snider-Pellegrini published his book, *La Création et ses mystères dévoilés* ("The Creation and its Mysteries Unveiled"). He proposed that all of the continents were once connected together during the Pennsylvanian Period. He based this theory on the fact that he had found plant fossils in both Europe and the United States that were identical. He found matching fossils on all of the continents.



https://peoplepill.com/

Scientific developments

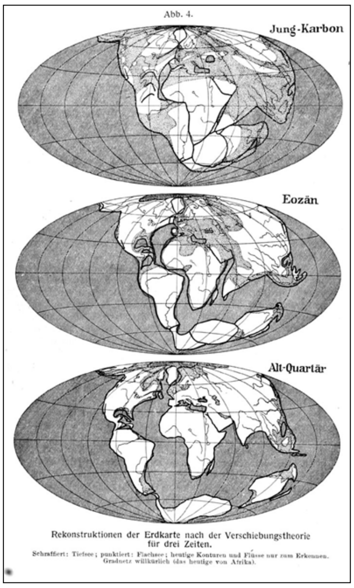
Alfred Lothar Wegener (1880-1930), a German polar researcher and geologist proposed "***CONTINENTAL DRIFT***" in **1910** and coined a term Urkontinent (Primal Continent / Pangaea: All-Earth).

… received heavy criticisms

In **1913** he published his book "*Die Entstehung der Kontinente und Ozeane*" with evidences to support his theory. I an series of later editions, he revised and polished his arguments (last edition, 1929).

… received heavier criticisms

Alfred died in 1930 during an expedition in Greenland.



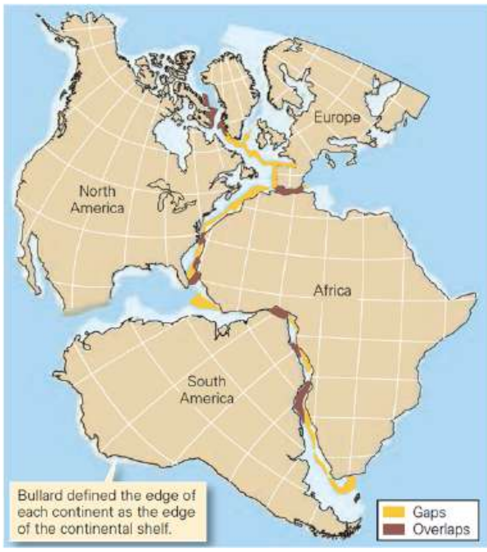
Evidence A: Fit of the Continents

Before Wegener, geologists viewed the continents and oceans as "immobile"-fixed in position throughout geologic time.

After a convincing world map (~1500); scientists observed that:

- Northwestern coast of Africa looks like it could tuck in against the eastern coast of North America, and the bulge of eastern South America could nestle cozily into the indentation of southwestern Africa.
- Australia, Antarctica, and India could all connect to the southeast of Africa, while Greenland, Europe, and Asia could pack against the northeastern margin of North America.

CRITICISM: Fine, but what moved the heavy continents apart?



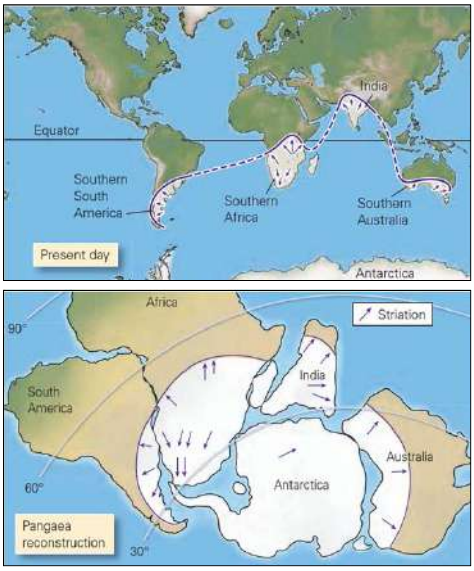
Evidence B: Locations of Past Glacier Deposits

Glaciars deposit characteristic sediments and they srecord the palaeoflow (ancient flow) directions. When the ice melts, it leaves the characteristic sediment deposit. Thus, the occurrence such deposits at a location serve as evidence that the location was covered by a glacier in the past. Large areas of land were covered by glaciers during discrete time intervals of Earth history called *ice ages*.

Wegener noticed glacier deposits in South America, southern Africa, southern India, Antarctica, and southern Australia; also, most striations associated with these deposits seemed to point from the sea into the continents (exact reverse of the present day condition.

This is only possible if continents had been united in Pangaea, with the southern part of Pangaea lying at polar latitudes.

CRITICISM: Fine, but what moved the heavy continents apart?



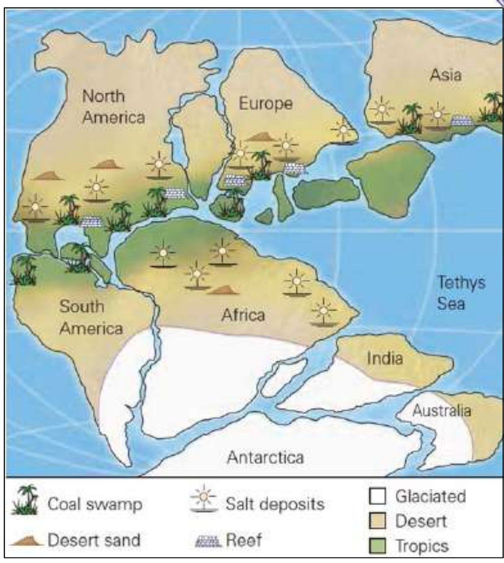
Evidence C: Distribution of Climatic Belts

If the southern part of Pangaea had straddled the South Pole, then, southern North America, southern Europe, and northwestern Africa would have straddled the equator and would have had tropical or subtropical climates.

- In the jungles of tropical regions, thick deposits of plant materials transformed into coal and hydrocarbons (can migrate).
- In the clear, shallow seas of tropical regions, large reefs made from the shells of marine organisms develop.
- In subtropical regions, on either side of the tropical belt, where desert climates exist, salt deposits.

The distribution of late Paleozoic coal, reef, sand-dune, and salt deposits could define climate belts on Pangaea.

CRITICISM: Fine, but what moved the heavy continents apart?

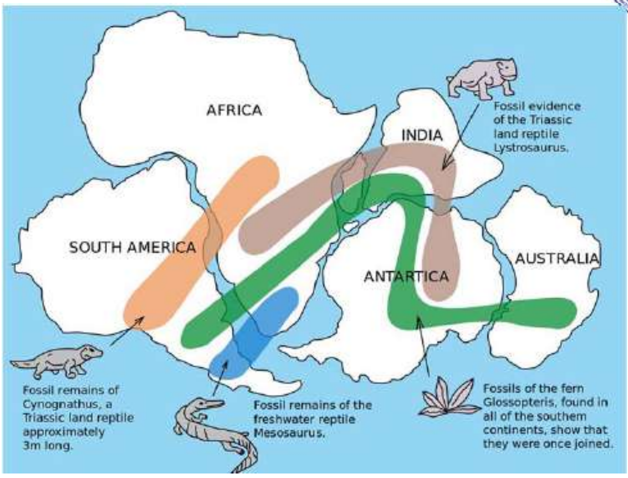


Evidence D: Distribution of Fossils

Land dwelling animals and plants cannot swim across vast oceans and they evolve independently on different continents. During a period of Earth history when all continents were in contact, however, land animals and plants could have migrated relatively easily among many continents.

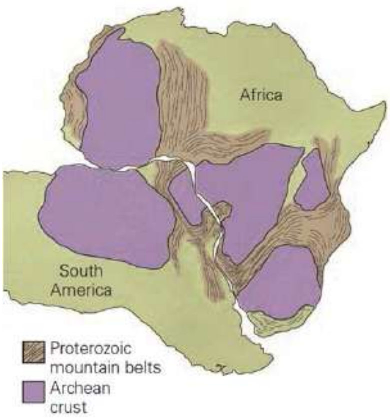
Fossil occurrences of land-dwelling species that existed during the late Paleozoic and early Mesozoic Eras (between 300 and 210 Ma) reveal that these species had indeed existed on several continents.

This requires the continents to have been adjacent to one another in the late Paleozoic and early Mesozoic Eras



CRITICISM: Well, could best be explained by these being fixed land masses which over time were connected and disconnected by periodic flooding; birds can carry the seeds. Even then, what moved the heavy continents apart?

More Evidences: Matching Geological units



The same distinctive Precambrian (before 541Ma) rock assemblages occurred on the eastern coast of South America and the western coast of Africa, regions now separated by an ocean.

The Appalachian mountain belt of the USA and Canada closely resemble those of mountain belts in southern Greenland, Great Britain, Scandinavia, and northwestern Africa regions.

Wegener's further arguments

Wegener had compiled a strong case for continental drift. But, he could not adequately explain how or why continents moved.

Wegener's writings gave the impression that continents somehow "plowed" through the ocean floor like the keel of a ship plows through water, but that's not possible because ocean floor rock is too strong.

Wegener also suggested that centrifugal force, due to the Earth's spin, drove continental movement, but that's not possible because the force isn't strong enough.

… it took 30 more years after Wegener's death, to prove that his theory was correct. In these 30 years, geologists learned how to determine the age of rocks, how to analyze *earth's past magnetic field (palaeomagnetism)* and how to "see" the ocean floor (bathymetry).

Next Lecture

Wegener was correct !!

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ES0213A: Fundamentals of Earth Sciences

Lecture 09. Concept of Plate Tectonics - II

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Palaeo-magnetism & Magnetic Inclinations as an evidence of Continental Drift
- Sea-Floor Spreading
- Scientific evidences of Plate Tectonics

Reference: Chapter 3, Marshak's Book

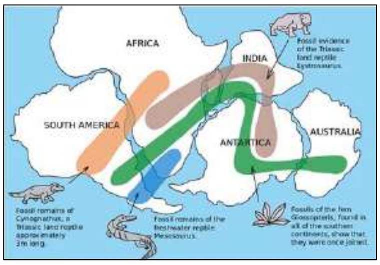
A Quick Review

Wegener Proposed the model of CONTINENTAL DRIFT; suggested a number of convincing evidences, but failed to provide the mechanism of continental drift.

Matching boundaries of the continents

Similar Climatic Zones

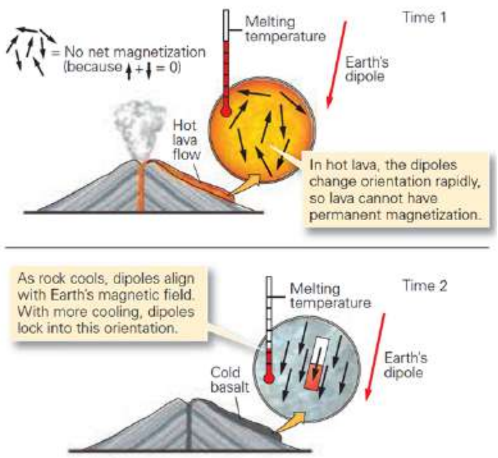
Similar Glacier Deposits



Similar Fossil records

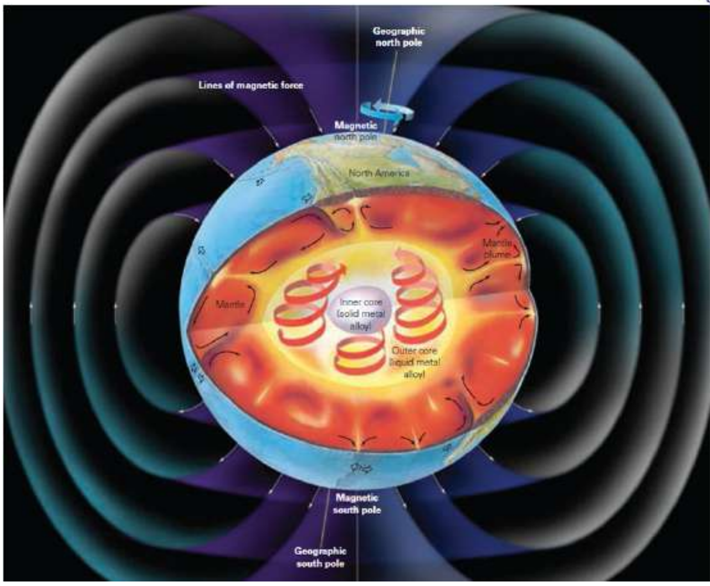
Palaeomagnetism - Introduction

- A few rocks in the Earth contain magnetic minerals (e.g., magnetite). They behave like magnets (strong/weak).
- These magnetic minerals, when crystallize from melt or deposit as sediments, align themselves along the Earth's magnetic field.
- The study of such magnetic behaviour led to the realization that rocks preserve **paleomagnetism**, a record of Earth's magnetic field in the past.
- The understanding of paleomagnetism provided proof of continental drift and, contributed to the development of plate tectonics theory.



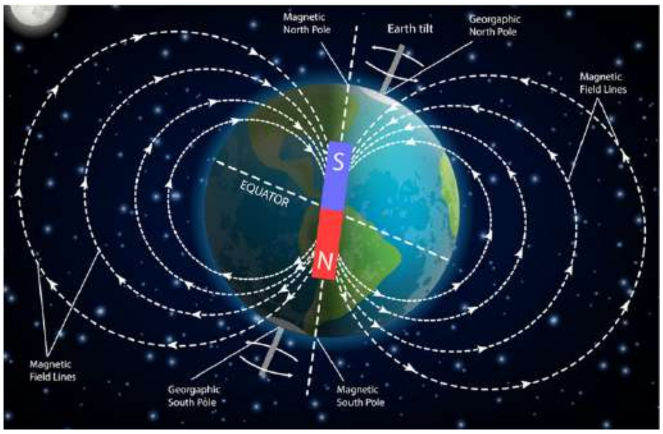
Earth's Magnetic Field

- The circulating liquid outer core (Fe-alloy) is responsible for the Earth's Magnetic field.
- Earth's magnetic field is similar like a bar magnet, which has two ends of opposite polarity – Magnetic dipole.



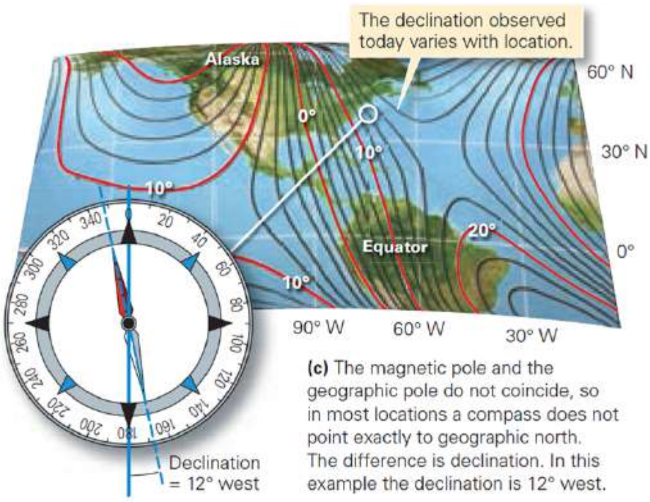
Earth's Magnetic Field

- Earth's dipole intersects the surface of the planet at two points, known as the **magnetic poles**.
- By convention, the north magnetic pole lies at the end of the Earth nearest the north geographic pole (the point where the northern end of the spin axis intersects the surface), so that the north-seeking (red) end of a compass needle points to the north magnetic pole.



Earth's Magnetic Field

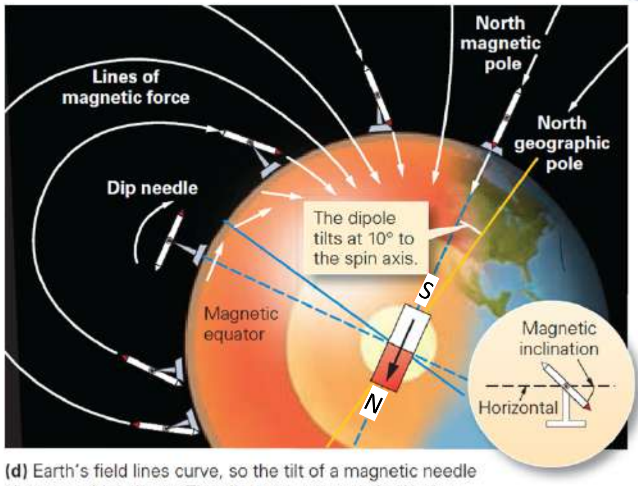
- As the geographic and Magnetic North directions do not coincide, the compass does not point exactly to geographic north. The angle between the direction that a compass needle points and a line of longitude at a given location is the **magnetic declination.** [the magnitude is not constant in time]



(c) The magnetic pole and the geographic pole do not coincide, so in most locations a compass does not point exactly to geographic north. The difference is declination. In this example the declination is 12° west.

Earth's Magnetic Field

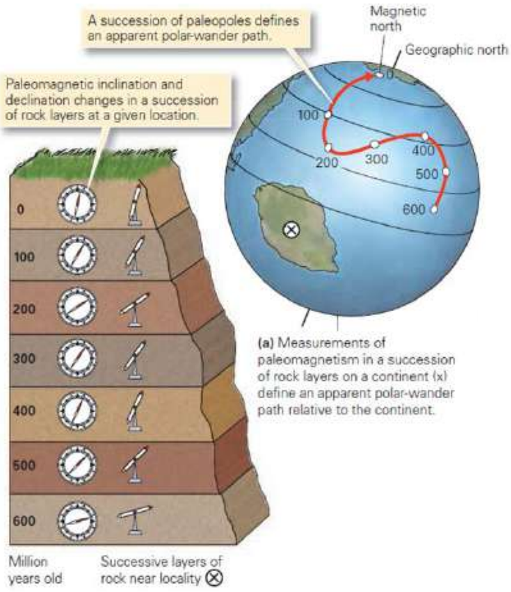
- Magnetic field lines curve through space between the magnetic poles. In a cross-sectional view,
  - Lines lie parallel (horizontal) to the surface of the Earth at the equator,
  - Lines tilt at an angle (inclined) to the surface in mid-latitudes,
  - Lines plunge perpendicular to the surface at the magnetic poles.
- The angle between a magnetic field line and the surface of the Earth, at a given location, is called the **magnetic inclination**.



(d) Earth's field lines curve, so the tilt of a magnetic needle changes with latitude. This tilt is the magnetic inclination.

Palaeomagnetism

- Earth's magnetic field is recorded and permanently stored by the magnetic minerals in rocks
- Geologists found that the paleomagnetic dipole in older rocks doesn't match always with the present day magnetic field. They concluded that the orientation of the Earth's magnetic dipole in the past was much different than it is today and thus that the magnetic poles were not necessarily close to the geographic poles (**Palaeopoles**).
- Geologists measured paleomagnetism in a succession of rocks of different ages from the same general location on a continent, and they plotted the location of the associated succession of paleopole positions on a map. The successive positions of dated paleopoles trace out a curving line that came to be known as an **apparent polar-wander path**.



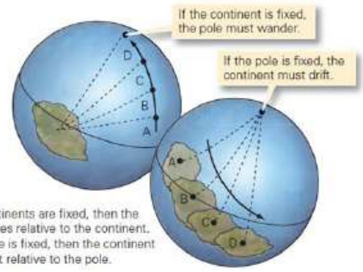
(a) Measurements of paleomagnetism in a succession of rock layers on a continent (x) define an apparent polar-wander path relative to the continent.

Palaeomagnetism

- Interestingly, it was found the apparent polar wander paths of different continents of same age are different.
  --This challenged the concept of fixed continents
- It's not the pole that moves relative to fixed continents but rather the continents that move relative to a fixed pole.
- Each continent has its own unique polar-wander path, the continents must also be moving relative to one another.

Alfred Wegener was right !! However, the mechanism of the drift was still unknown.

(b) The apparent polar-wander path of North America is not the same as that of Europe or Africa.



(c) If continents are fixed, then the pole moves relative to the continent. If the pole is fixed, then the continent must drift relative to the pole.

Next Lecture

Sea-floor Spreading
and
Plate Tectonics

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ES0213A: Fundamentals of Earth Sciences

Lecture 10. Concept of Plate Tectonics - III

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Experimental Rock Deformation Laboratory

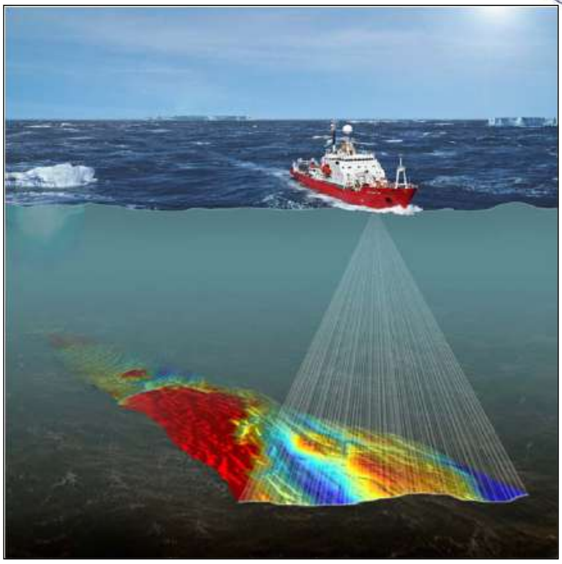
Aims of this lecture

- Sea-Floor Spreading
- Scientific evidences of Plate Tectonics
- Plate and Plate Boundaries

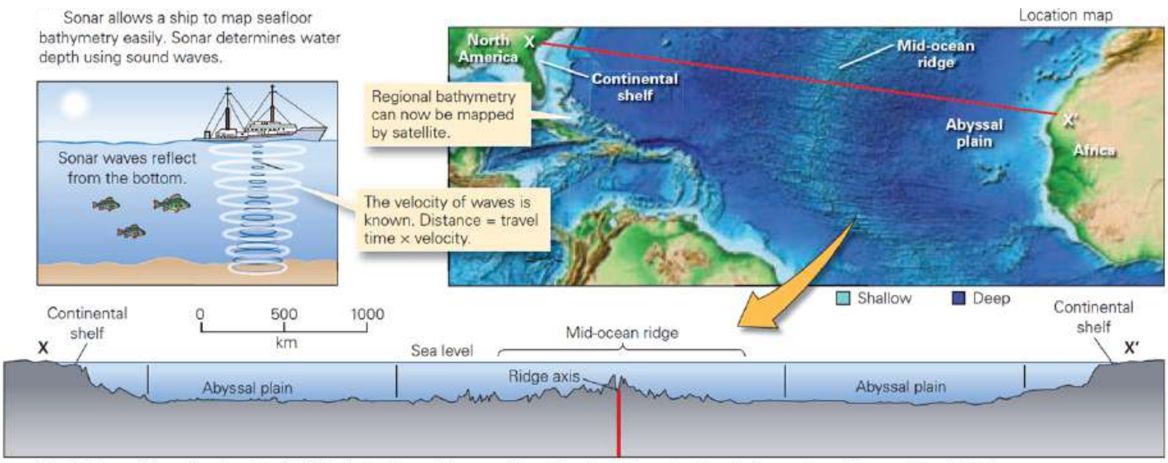
Reference: Chapter 3 & 4, Marshak's Book

Role of World War – II [1939-1945]

- Before the WW2, people had no idea about the floor of the oceans (topography, composition)
- Point measurements (dropping heavy objects with a long-long cable) was common. 360 such measurements in 5 years (1872-76) by HMS Challenger.
- Submarines were heavily introduced during the WW2. Navies required detailed information about bathymetry for smooth fleet of the submarines. The invention of ***sonar*** (echo sounding) permitted such information to be gathered quickly. ALSO OPENED A NEW WINDOW FOR GEOLOGISTS.



See the Sea-floor Bathymetry



A bathymetric profile along line X–X' illustrates how mid-ocean ridges rise above abyssal plains. Both are deeper than continental shelves.

Observations from Sea-floor Bathymetry

- Oceanic crust is quite different from continental crust, it is not flat but extremely rough.
- The sediment thickness: Thicker near the coastal region; thinner at the middle. The age of the base of the thickest sediments is very young (150-200 My or less).
- The sea-floor includes **Abyssal Plains**, broad flat regions (4 to 5 km depth), and **Mid-Ocean Ridges (MOR)**, elongate, hot, symmetrical submarine mountain ranges whose peaks, with a depression, lie about 2 to 2.5 km below sea level. The tip of the mid-ocean ridges are ridge-axes. [Features of Atlantic]
- Along the perimeter of the Pacific Ocean, and at several other localities, the ocean floor depths are greater than 5 km; these are elongate troughs (**Trenches**). All the trenches border **Volcanic Arcs**, curving chains of active volcanoes. Numerous volcanic islands poke up from the ocean floor, and not always along volcanic island arcs (**Seamounts**).
- The mid-ocean ridges are sliced and shifted laterally by number of vertical fractures (**Fracture Zones**)
- Most of the earthquakes and volcanisms happen along the Mid-Oceanic Ridges, Fracture Zones and Trenches

Let's look at some of these features in Google Earth !!

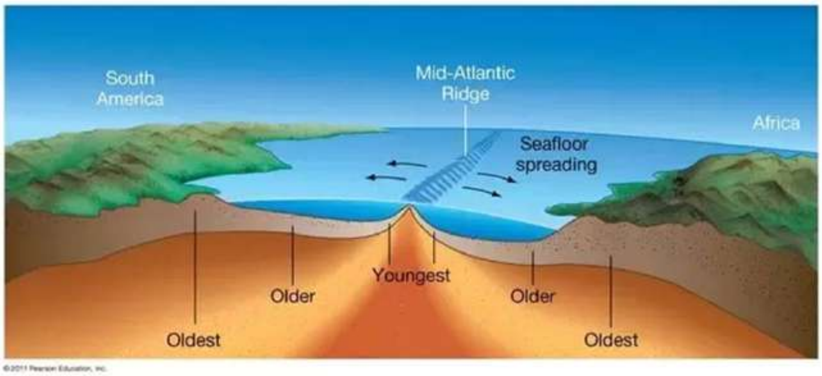
Sea-floor Spreading and Harry Hess

- The age of the base of the thickest sediments is very young (150-200 My or less) → **Ocean Floor must be younger than continents.**
- The sediment thickness is thicker near the coastal region; thinner at the middle → **the MOR are younger than the deeper parts of the ocean floor.**

New Oceanic Crust must be forming at the MORs and the oceans could be wider with time. BUT HOW??

- Earthquakes and volcanisms happen along the Mid-Oceanic Ridges, Fracture Zones → **Sea-floor breaking and addition of new materials.**
- High heat flow along the MORs → **molten rock rising up beneath ridges and that the seafloor crust was stretching**
- **In 1960, Hess** proposed that this material from the mantle rose beneath mid-ocean ridges; that at the ridge axis melt derived from the mantle solidified to form oceanic crust; and that, once formed, the new crust cracked, split apart, and moved away from the ridge – **SEA-FLOOR SPREADING** (*R. Dietz)*

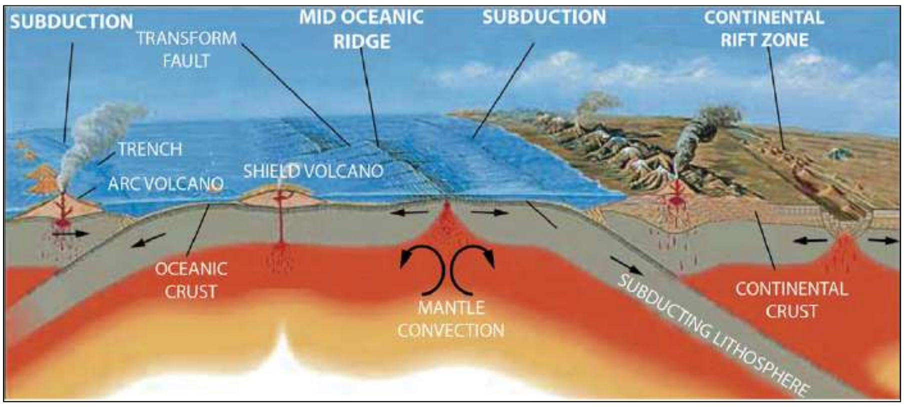
Sea-floor Spreading



PROBLEM CONTINUES: if new ocean floor formed, old ocean floor must be consumed or destroyed somewhere, or the Earth's circumference would have to increase, but earth's diameter is more or less constant with time.

Sea-floor Subduction

Earthquakes also occur along the Trenches → **the places where the seafloor sank back into the mantle and that the earthquakes occurring at trenches were evidence of this movement.. The SUBDUCTION ZONES.**



Hypothesis:

Rising magma erupts at the MOR.

New oceanic crust moves away from the MOR; sediments deposit.

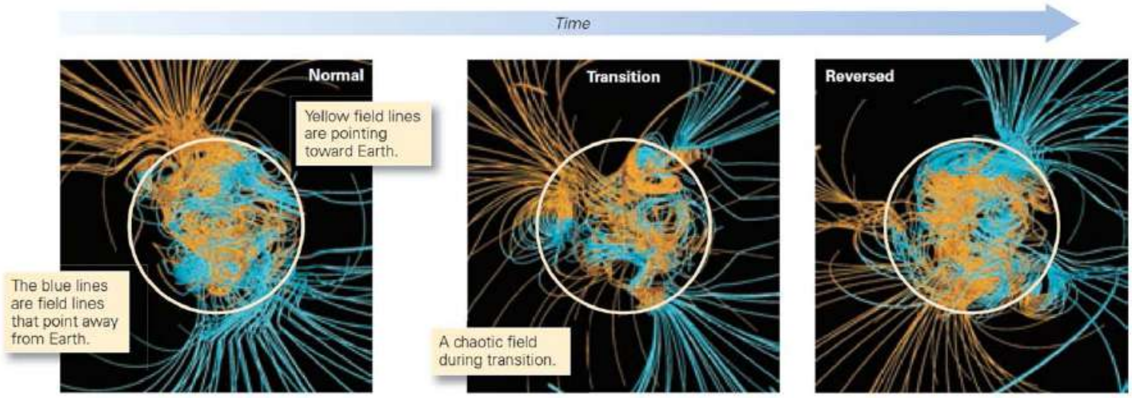
Sea-floors are driven back in to the mantle at trenches through subduction.

The continental drift and seafloor spreading were convincing including the mechanisms, but it must be tested.

Evidence of Sea-floor Spreading

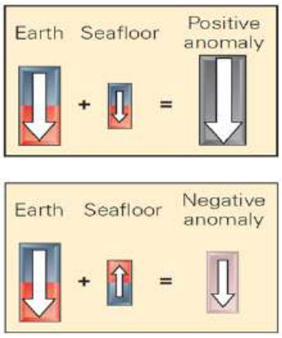
Marine Magnetic Anomalies and Magnetic Pole Reversals

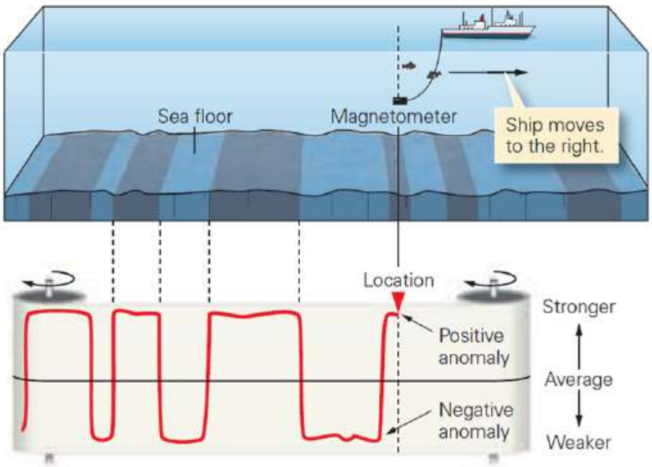
If the new oceanic crusts are being formed continuously at the MOR, the magnetic minerals of the oceanic crust should record and store the magnetic histories of the Earth !



Evidence of Sea-floor Spreading

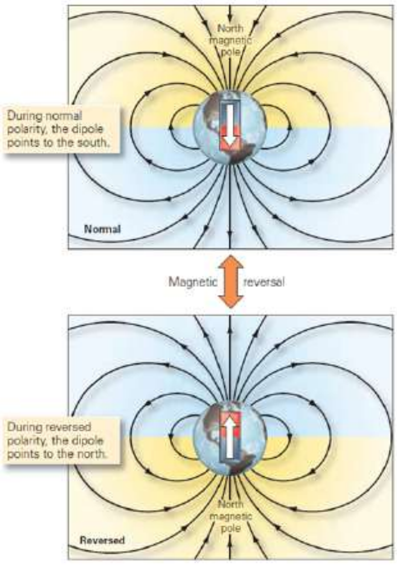
Marine Magnetic Anomalies and Magnetic Pole Reversals

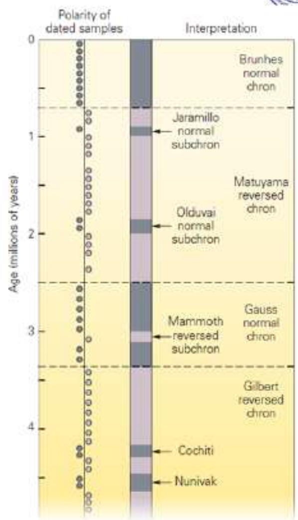




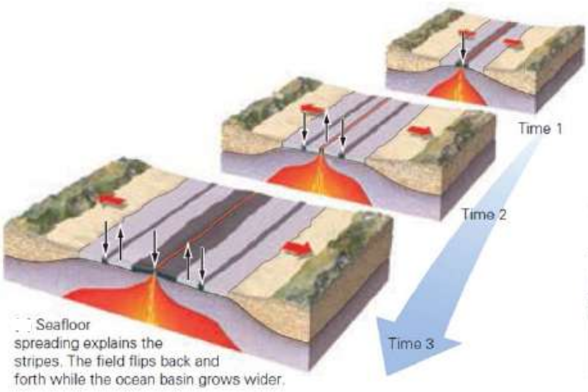
Evidence of Sea-floor Spreading

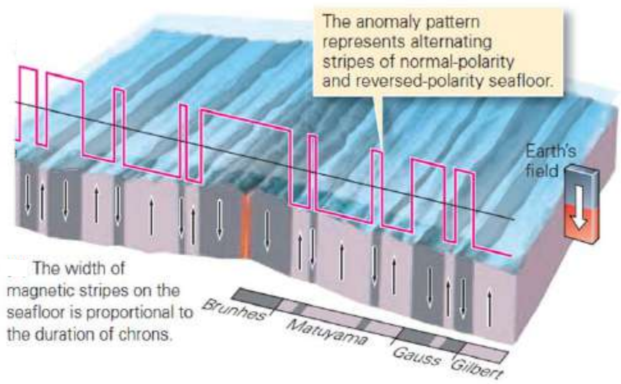
- Reversals do not occur periodically, the time intervals between reversals (**polarity chrons)**, are different.
- The last change from reverse to normal happened about 700,000 years ago and we are living in a normal polarity chron… the time that *Homo erectus*, who first learned to control fire.
- The youngest four polarity chrons (Brunhes, Matuyama, Gauss, and Gilbert) are named after scientists who made important contributions to the study of rock magnetism.



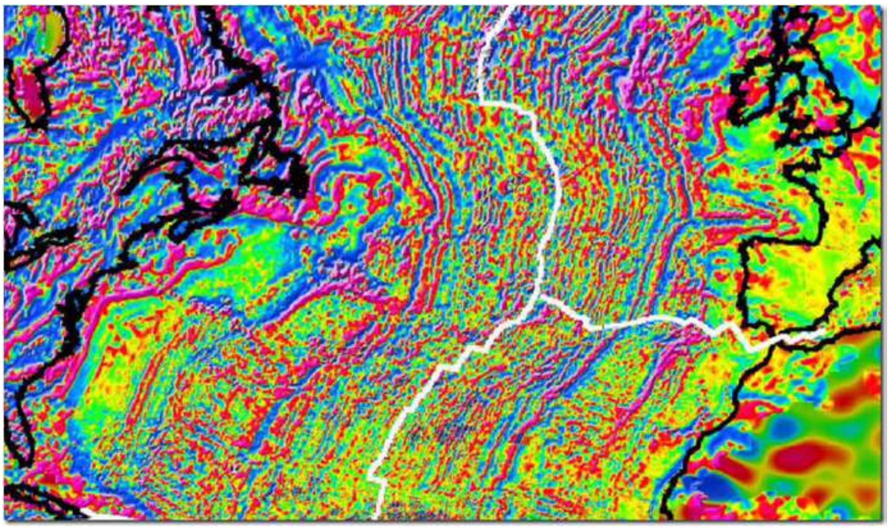


Evidence of Sea-floor Spreading





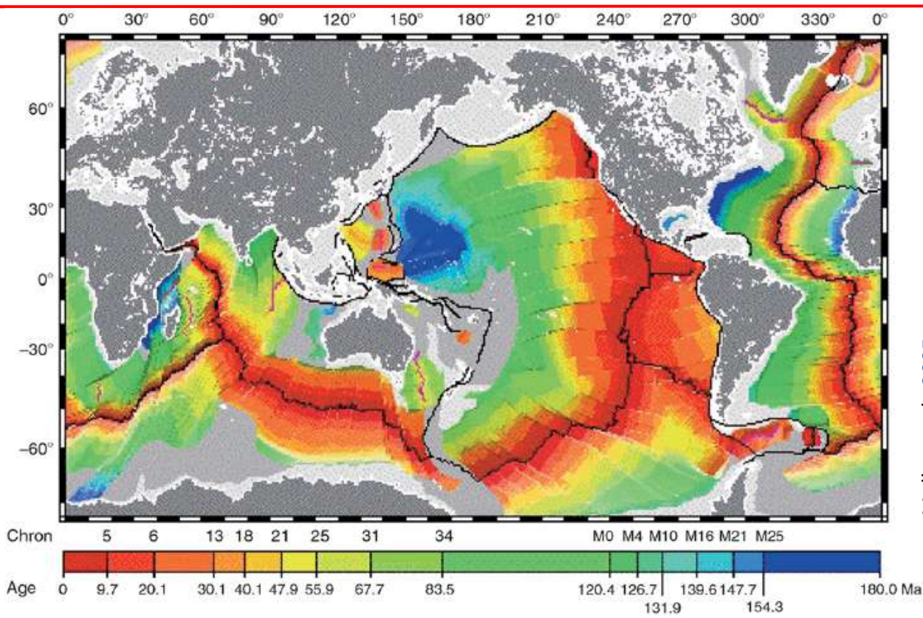
Evidence of Sea-floor Spreading



Magnetic Anomaly Map of Atlantic (Korhonen, et al., 2007,)

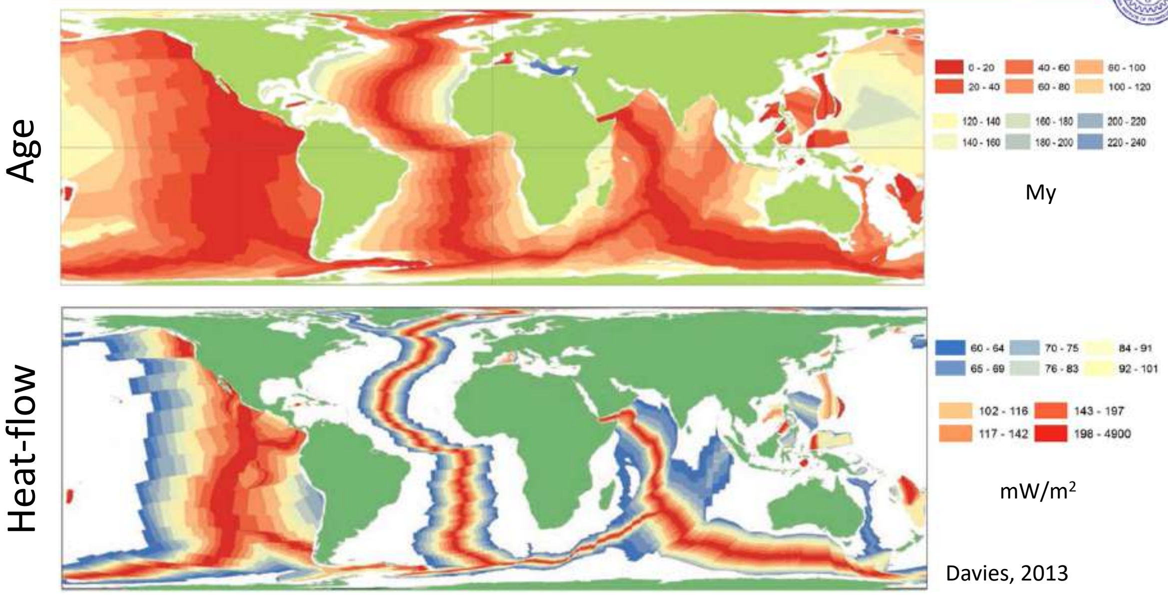
Evidence of Sea-floor Spreading

Age of the Sea-Floors



Muller *et al.*, 2005

Evidence of Sea-floor Spreading



Davies, 2013

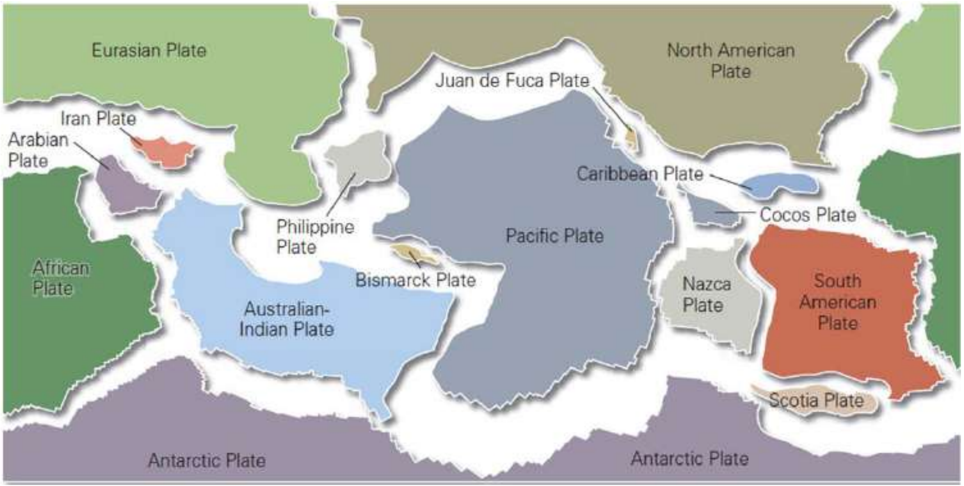
What is Plate Tectonics?

- The **lithosphere**, which consists of the crust plus the uppermost part of the upper mantle, behaves as a relatively hard layer, meaning that when a force pushes or pulls on it flow but rather bends or breaks.
- The **lithosphere** is discontinuous and broken in to pieces… which are known as **PLATES**
- The contact of the plates are knows as **PLATE BOUNDARIES.**
- The PLATES move relative to each other along the **PLATE BOUNDARIES.**

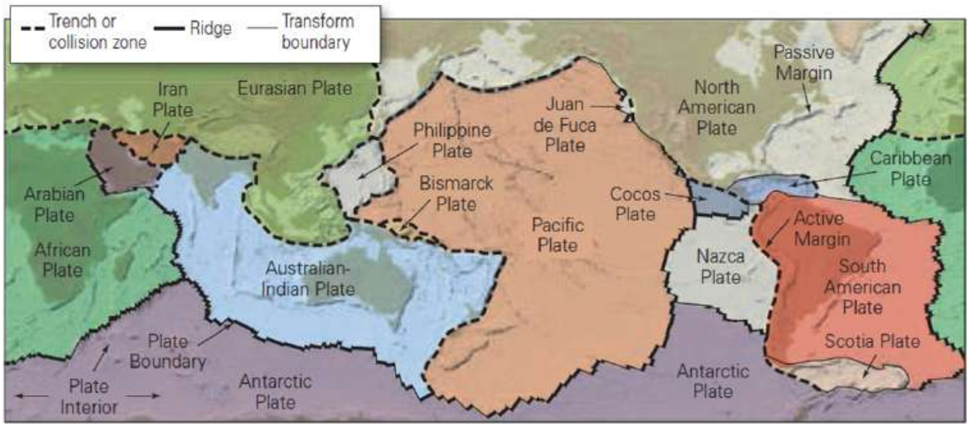
The entire process is known as PLATE TECTONICS

Why do the plates move? The quick answer is: due to MANTLE CONVECTION. We shall learn more later on this.

Major Plates of the Earth



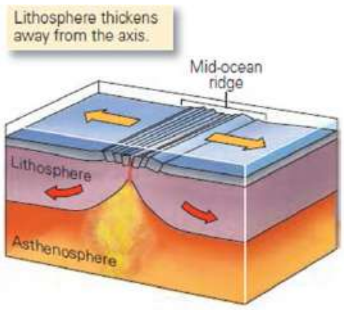
Major Plates of the Earth



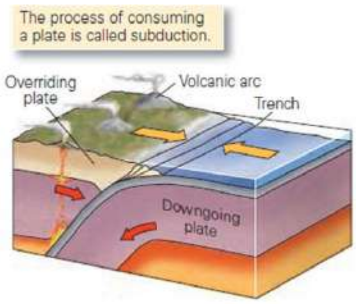
Some consist entirely of oceanic lithosphere, whereas others consist of both continental and oceanic lithosphere.

Plate Boundaries

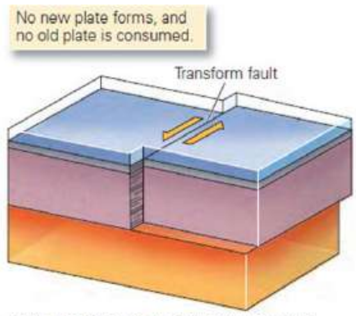
- **Divergent Plate Boundary**
- **Convergent Plate Boundaries**
- **Transform/Sliding Plate Boundaries**



(a) At a divergent boundary, two plates move away from the axis of a mid-ocean ridge. New oceanic lithosphere forms.



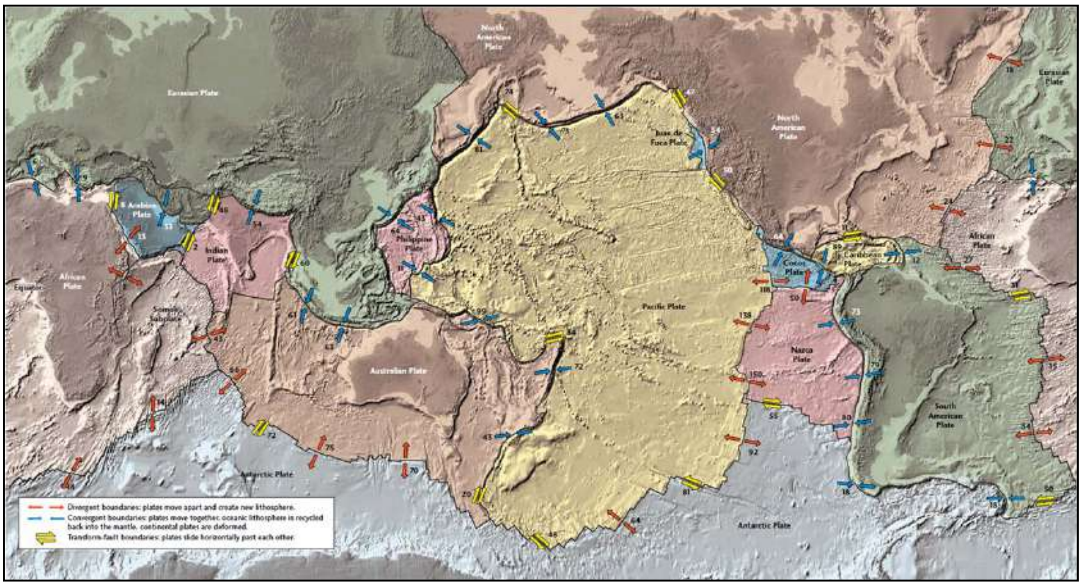
(b) At a convergent boundary, two plates move toward each other; the downgoing plate sinks beneath the overriding plate.



(c) At a transform boundary, two plates slide past each other on a vertical fault surface.

Areas of modern & challenging research

Global Plate Boundaries and Plate Velocities



Alfred Wegener Song !!

https://www.youtube.com/watch?v=T1-cES1Ekto

Next Lecture

Minerals
and
Rocks

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ES0213A: Fundamentals of Earth Sciences

Lecture 11. Atomic Structures of Matters

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Historical developments on the concept of Matter
- The basic structure of Matters
- Definition and Idea of Minerals

Reference:
Chapter 3, Grotzinger_Jordan's Book
Chapter 5, Marshak's Book

FROM NOW ON, YOU WILL BE FLOODED WITH NAMES AND TERMINOLOGIES ….

Instructor's advice: Take is easy.. spend little time and keep patience

Historical Developments

- The idea of the matters and their forms originated from the Greek Philosophgers (Plato, Aristotle).
- Greeks though of 4 basic elements: Fire, Air, Water and Earth
- Greeks though of 4 basic elements: Fire, Air, Water and Earth
(a similar idea was there also in Vedas, much later, though: ***kshiti*** *[soil],* ***ap*** *[water],* ***tej*** *[light],* ***marut*** *[air]* and ***byom*** *[space]* and the processes as ***sattwa*** *[illumination],* ***rajas*** *[active]* and ***tamas*** *[static]*)
- Democritus is credited with coming up with the concept of ***atom*** …. "if you keep breaking something down, you would get to a size that could no longer be broken. This would be the indivisible piece. In Greek, atomos = indivisible"
- Interestingly, the Aristotelian view of the composition of matter was popular for over two thousand years, and the idea of Demicritus of atom was suppressed.

Historical Developments

- English schoolteacher John Dalton proposed his hypothesis that the behaviour of matter could be explained using an atomic theory, published in 1907.
    - Matter is composed of exceedingly small particles called atoms. An atom is the smallest unit of an element that can participate in a chemical change.
    - An element consists of only one type of atom, with a characteristic mass of the element and is the same for all atoms of that element. A macroscopic sample of an element contains an incredibly large number of atoms, all of which have identical chemical properties.
    - Atoms of one element differ in properties from atoms of all other elements.
    - A compound consists of atoms of two or more elements combined in a small, whole-number ratio. In a given compound, the numbers of atoms of each of its elements are always present in the same ratio
    - Atoms are neither created nor destroyed during a chemical change, but are instead rearranged to yield substances that are different from those present before the change.

Historical Developments

- If matter were composed of atoms, what were atoms composed of? Were they the smallest particles, or was there something smaller?
- J J Thompson experimented with a gas-filled cathode ray tube and concluded there mist be negatively charged particle inside the atoms and the particles are much smaller and lighter.. Discovery of ELECTRONS.
- The next major development by Ernest Rutherford, who experimented with a beam of high-speed, positively charged α particles to a thin gold foil and found most particles passed through the foil, but a few of then showed deviation and total deflection – discovery of positively charged NUCLEUS, also the most the volume occupied by an atom is empty, and protons.
- In 1932, James Chadwick found evidence of neutrons, uncharged, subatomic particles with a mass approximately the same as that of protons.

Some terminologies and their meanings

- **ELEMENTS:** A pure substance that cannot be separated into other materials is an **element**. There are 92 natural elements and can be represented in a periodic table. The elements have names and symbols.
- **ATOMS & COMPONENTS:** The smallest segment of an element retaining the characteristics of the element is an **atom**. At the centre of each atom the is a dense *nucleus* containing virtually all the mass of the atom in two kinds of particles: **protons** (positively charged) and **neutrons** (electrically inert). An atom consists of a nucleus surrounded by a cloud of orbiting **electrons** (negatively charged).
- **ATOMIC NUMBER:** The number of protons in the nucleus of an atom is its **atomic number.**
- **ATOMIC MASS:** The **atomic mass** of an element is the sum of the masses of its protons and its neutrons.
- **ISOTOPES:** Atoms of an element that have differing numbers of neutrons (but a constant atomic number) are called **isotopes.** [Carbon has six protons, but may contain six, seven, or eight neutrons, giving atomic masses of 12, 13, and 14.]
- **MOLECULES:** The smallest particle of an element or a compound, which is capable to exist independently and shows all the properties of the respective substance. A molecule, normally, is a group of two or more atoms (same or different elements) which are chemically bonded together.

Some terminologies and their meanings

- **CHEMICAL BOND:** A molecule or compound is formed either by electron sharing or by electron transfer, the ions or atoms that make up the compound are held together by some attractions – Chemical Bonds.
  - IONIC BONDS: The electrostatic attraction between ions of opposite charge, such as Na^+ and Cl^- in sodium chloride
  - COVALENT BONDS: Atoms held together in ccompounds by sharing electrons by covalent bonds and are stronger than ionic bonds.
  - METALIC BONDS: Mostly with metallic elements which lose electrons and the free electron sharing results kind of covalent bonds.
- **Some other terms:**
  Ion; Anion; Cation; State of Matter; Changing of State; Chemical Formula; Chemical Reactions; Electron Transfer; Electron Sharing; Avogadro Number; Law of Conservation of Mass; Radioactivity; Van der Waals forces etc. (.. and if you are interested see also ***Antimatter*** and ***Dark Matter***).

Definition of a Mineral

- A **mineral** is a naturally occurring, homogeneous solid crystalline substance, usually inorganic, with a specific chemical composition.
  - Naturally occurring: Synthetic minerals are not considered minerals !!
  - *Solid crystalline substance:* neither liquids nor gases. When we say that a mineral is crystalline, we mean that the tiny particles of matter, or atoms, that compose it are arranged in an orderly, repeating, three-dimensional array (*glass, amorphous materials are not minerals*)
  - *Inorganic:* Coal is not a mineral..
  - *Chemical Composition:* A mineral's chemical composition either is fixed or varies within defined limits and possible to write the chemical formula of a mineral.

QUARTZ

SiO_2

OLIVINE

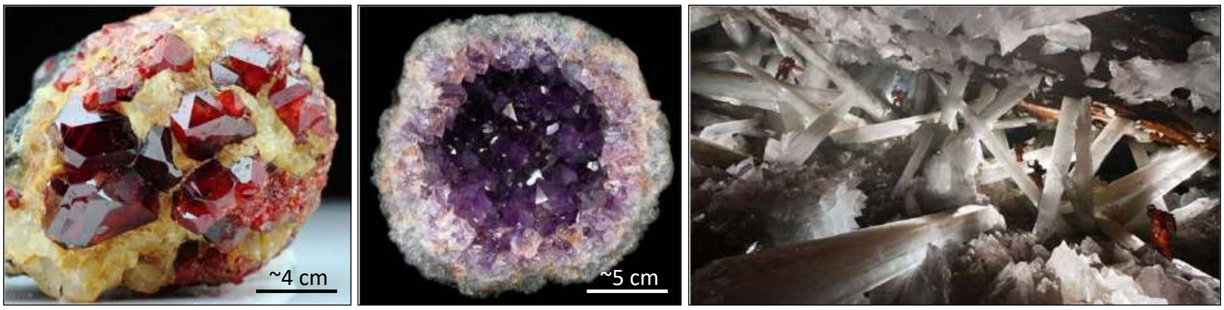
$(Mg, Fe)_2SiO_4$

Forsterite: Mg_2SiO_4
Fayalite: Fe_2SiO_4

How does a mineral form?

- One can view the minerals either in microscale (submicroscopic atoms organized in an ordered three-dimensional array) or in macroscale (crystals that we can see with the naked eye… crystals can me microscopic, too).

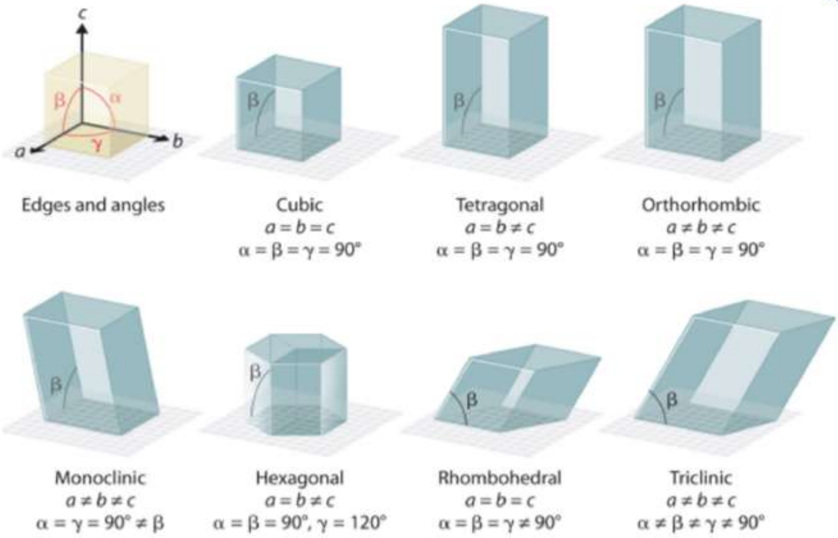
- Minerals from by crystallization – (A) from melt/magma; (B) precipitation from fluid and (C) Solid-state transformation. During crystallization, the initially microscopic crystals grow larger, maintaining their crystal faces (flat boundaries of crystals) as long as they are free to grow. Pressure and Temperature are the crucial factors to govern the crystallization process.



Crystal Systems

- In Crystal Systems, the crystals are classified based on the length of the faces and their mutual interaction angles.

- The edge lengths of a crystal are represented by the letters ***a***, ***b***, and ***c***. The angles at which the faces intersect are represented by the Greek letters ***α***, ***β***, and ***γ***

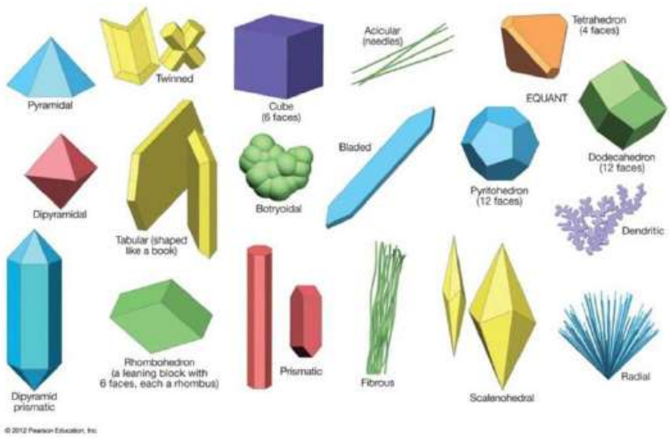


Read more on…

- CRYSTAL FORMS: General Form; Special Form; Open Form; Closed Form
- There are 48 possible forms of crystals that can be developed as the result of the 32 combinations of symmetry.

- A few names of the common forms are:

  Pedions; Pinacoids; Domes; Sphenoids; Prisms; Pyramids; Dipyramids; Trapezohedrons; Scalenohedrons; Rhombohedrons; Hexahedrons; Octahedrons; Dodecahedrons; Tetrahexahedron….



Next Lecture

Classification & Identification of Minerals

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 12. Minerals and Their Classifications

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Minerals
- Classification
- Silicate Minerals

<u>Reference:</u>
Chapter 3, Grotzinger_Jordan's Book
Chapter 5, Marshak's Book

Most images used in this presentation are from different web sources and a few are own collection

Minerals

Minerals are beautiful, pleasing, elegant and charming..








Minerals

Gold
(Au)

Labradorite (Plagioclase)
($(Ca,Na)(Al,Si)_4O_8$)

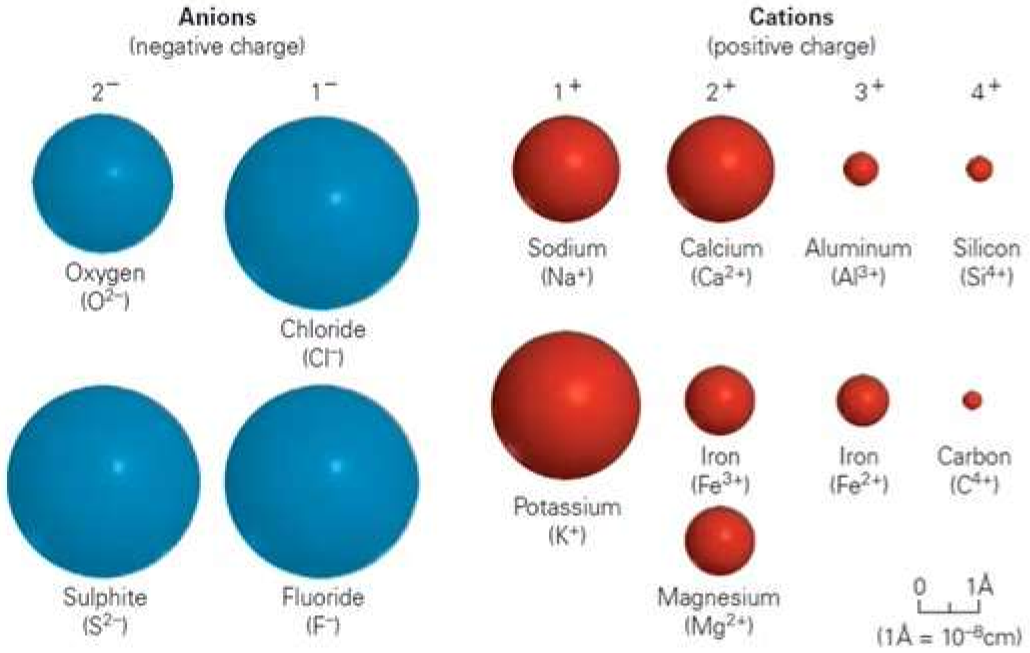
Muscovite (Mica)
$KAl_3Si_3O_{10}(OH)_2$

Hornblende
($(Ca,Na)_{2-3}(Mg,Fe,Al)_5(Si,Al)_8O_{22}(OH,F)_2$)

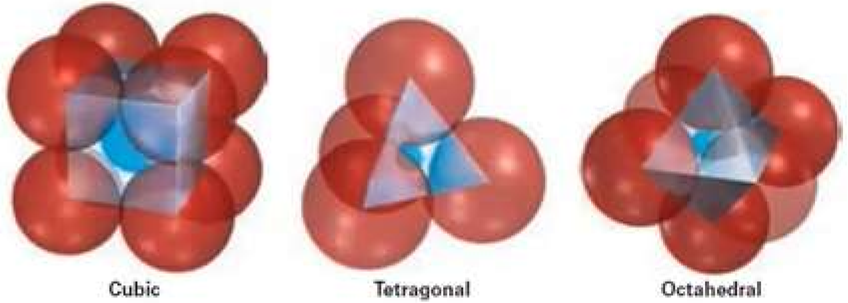
There are more than 3000-4000 known minerals !!

Minerals: Classification Scheme

- Like all objects in the world, we also classify Minerals based on their several physical properties. The most common of them is by specifying the principal anion or anionic group within the mineral (Baron Jöns Jacob Berzelius (1779–1848)).



Ions come in a wide range of sizes. The difference in size depends, in part, on the number of electrons they contain.



Ions can pack together in different ways. Each configuration can be described by a geometric shape.

Classification of Minerals

- **SILICATES**: The fundamental component of silicate minerals is the SiO_4^{4-} anionic group.

Quartz (SiO_2)

Feldspar ($KAlSi_3O_8$).

- **SULFIDES**: Sulfides consist of a metal cation bonded to a sulfide anion (S^{2-}).

Galena (PbS)

Pyrite (FeS_2)

- **OXIDES**: Oxides consist of metal cations bonded to oxygen anions. Typical oxide minerals include hematite (Fe_2O_3) and magnetite (Fe_3O_4).

Hematite (Fe_2O_3)

Magnetite (Fe_3O_4).

Classification of Minerals

- **HALIDES**: The anion in a halide is a halogen ion (such as chloride, Cl^-, or fluoride, F^-)

Halite ($NaCl$)

Fluorite (CaF_2)

- **CARBONATES**: In **carbonate minerals**, the molecule CO_3^{2-} serves as the anionic group.

Calcite ($CaCO_3$)

Dolomite ($CaMg[CO_3]^2$)

- **NATIVE METALS**: The metal atoms are bonded by metallic bonds.

Gold (Au)

Copper (Cu)

- **SULFATES**: Sulfates consist of metal cations bonded to SO_4^{2-} anionic groups.

Gypsum ($CaSO_4.2H_2O$)

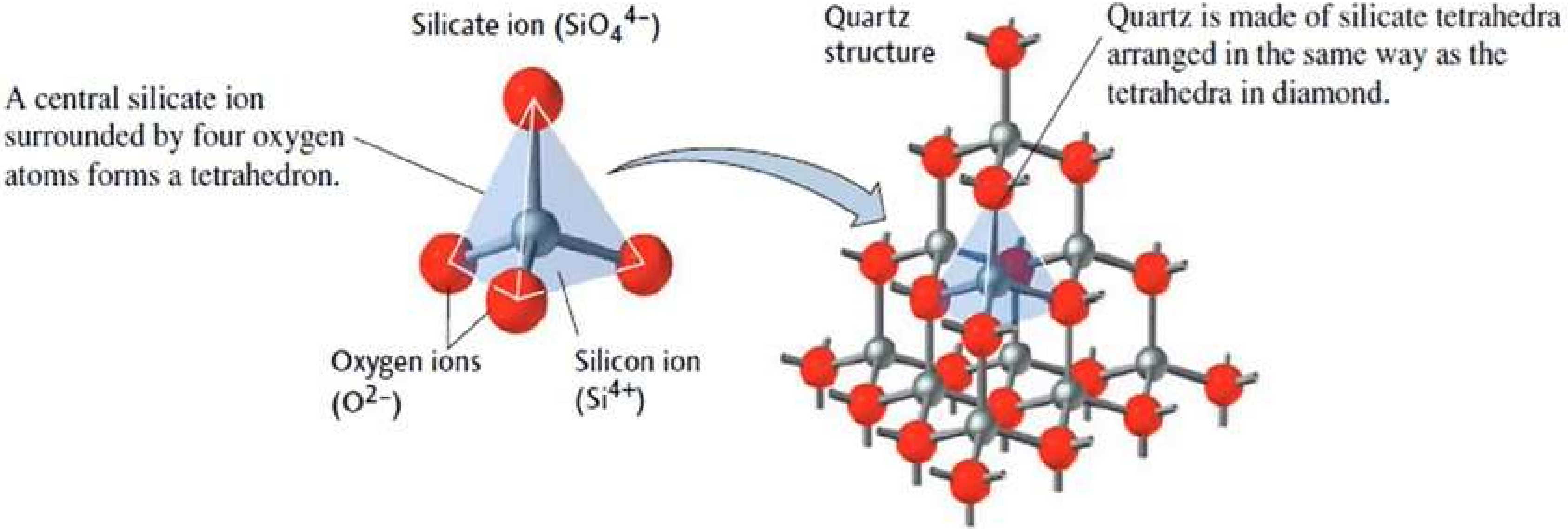
Anhydrite ($CaSO_4$)

Classification of Minerals

CLASS	DEFINING ANIONS	EXAMPLE
Silicates	Silicate ion (SiO_4^{4-})	Quartz (SiO_2)
Sulphides	Sulfide ion (S^{2-})	Pyrite (FeS_2)
Oxides	Oxygen ion (O^{2-})	Magnetite Fe_3O_4)
Halides	Chloride (Cl^-), fluoride (F^-),	Halite (NaCl)
Carbonates	Carbonate ion (CO_3^{2-})	Calcite ($CaCO_3$)
Native Metals	no charged ions	Gold (Au)
Sulphates	Sulfate ion (SO_4^{2-})	Gypsum $CaSO_4.2H_2O$)

Silicate Group of Minerals

- 95% of the earth's crust and almost entire mantle are made of silicate minerals
- In this group, four oxygen atoms surround a single silicon atom, thereby defining the corners of a tetrahedron, a pyramid-like shape with four triangular faces → Silica-Oxygen Tetrahedron

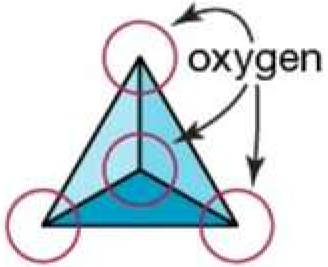


- The Silica-Oxygen Tetrahedron can be arranged in many different ways. The arrangement also determines the degree to which tetrahedra share oxygen atoms.

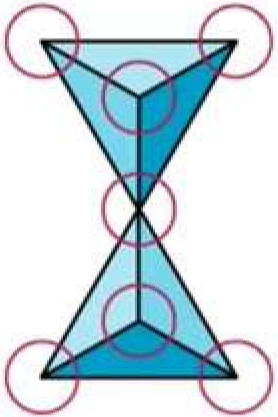
Silicate Group of Minerals

- ***Independent (Single/Double) tetrahedra:*** In this group, tetrahedra are independent and do not share any oxygen atoms. The attraction between the tetrahedra and positive ions holds crystals together. This group is also known as Nesosilicates (single) and Sarosilicates; also as Olivine Group.

Nesosilicates
Unit composition: $(SiO_4)^{4-}$
Example: olivine,
$(Mg, Fe)_2SiO_4$

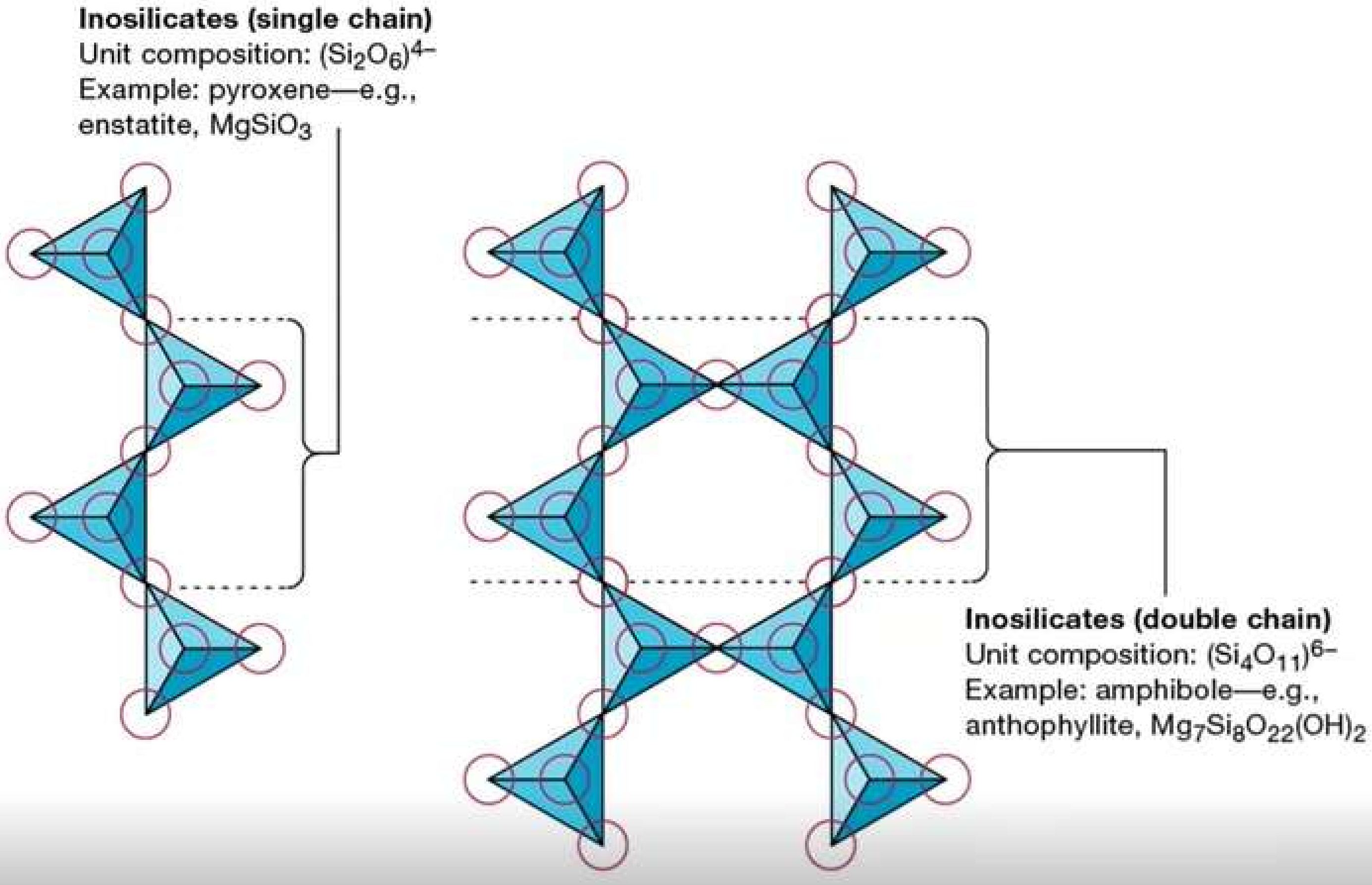


Sorosilicates
Unit composition: $(Si_2O_7)^{6-}$
Example: hemimorphite,
$Zn_4Si_2O_7(OH)_2 \cdot H_2O$



Silicate Group of Minerals

- ***Chain Silicates:*** In a single-chain silicate, tetrahedra link to form a chain by sharing two oxygen atoms; in a double-chain silicate, tetrahedra link to form a double chain by sharing two or three oxygen atoms. Also known as Inosilicates.

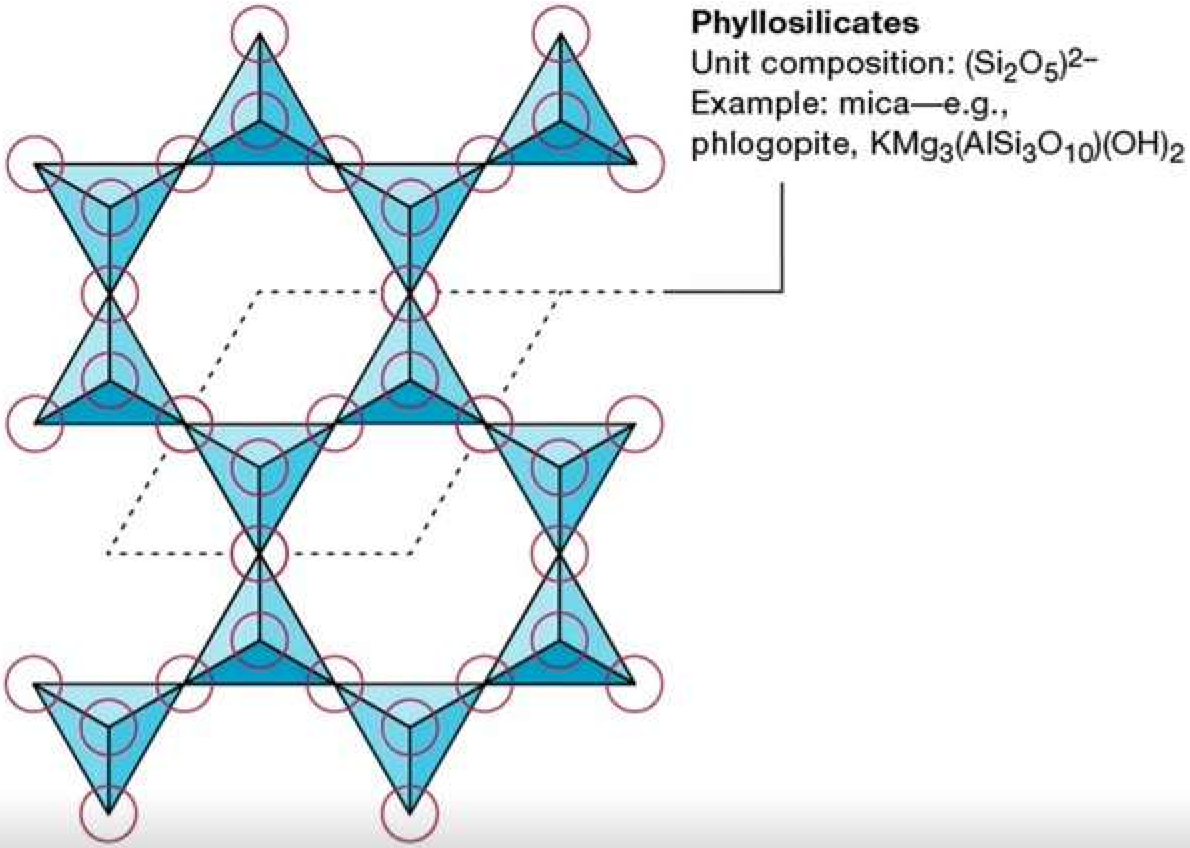


<u>Single Chain:</u>
PYROXENE

<u>Double Chain:</u>
Amphibole

Silicate Group of Minerals

- ***Sheet Silicates:*** Tetrahedra in this group share three oxygen atoms and therefore link to form two-dimensional sheets. Other ions fit between the sheets in sheet silicates. Also known as Phyllosilicates or Mica Group of minerals.



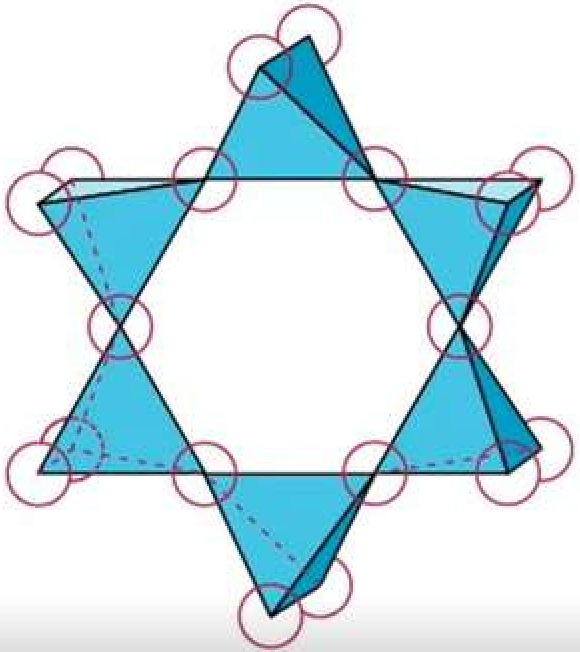
Examples:

Muscovite, Biotite, Clay minerals

Silicate Group of Minerals

- ***Ring silicates:*** This group of minerals have three or more tetrahedra linked in a ring. Also known as Cyclosilicates.

Cyclosilicates
Unit composition: $(Si_6O_{18})^{12-}$
Example: beryl,
$Be_3Al_2Si_6O_{18}$

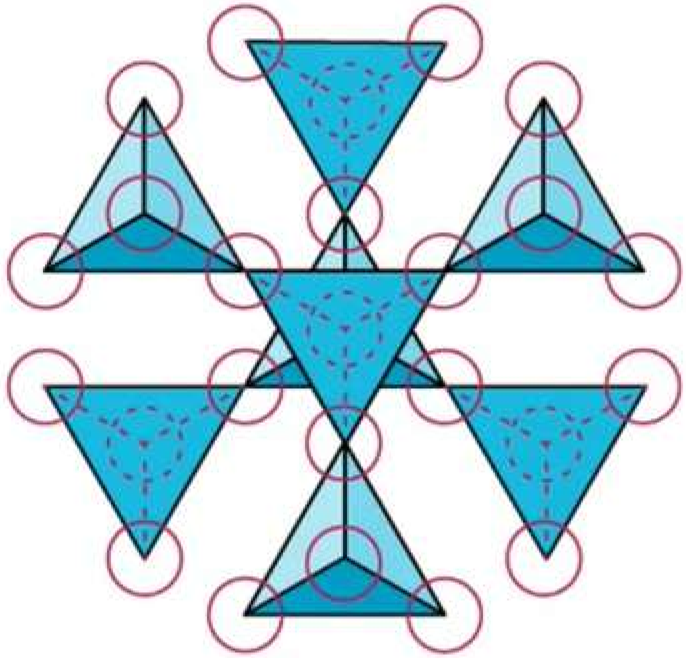


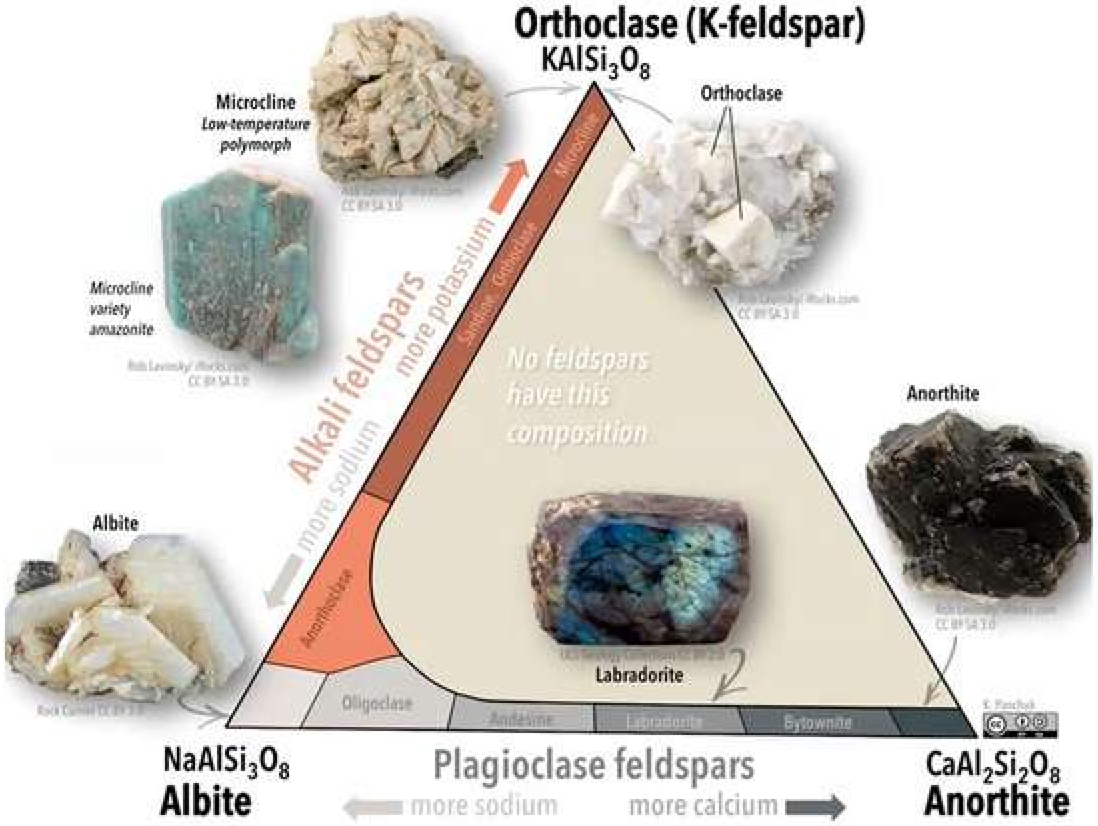
Examples:
Beryl

Silicate Group of Minerals

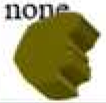
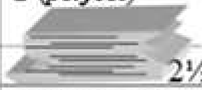
- ***Framework silicates:*** In a framework silicate, each tetrahedron shares all four oxygen atoms with its neighbours, forming a three-dimensional structure. Also known as Tectosilicates.

Tectosilicates
Unit composition: $(SiO_4)^{4-}$
Example: high cristobalite, SiO_2





Silicate Group of Minerals: Summary

Silicate Structure	Example Mineral	Silica Content (%SiO_2)	Fe/Mg‡ Content	Al† content	Cleavage Hardness	Density Color	‡Ferromagnesians †Alluminosilicates
Isolated Silicates	Olivine	~16%	~50% ‡	0%	none  6½	~4 g/cm³ green	Comprises most of the ***Mantle***
Single Chain Silicates	***Pyroxene***# Group (e.g., Augite)	25-50%	18-26% ‡	0-16% (†)	2 (90°)  5½	~3.3 black	Found in <u>basalt</u> ***<u>Oceanic Curst</u>*** with ***Ca-Plag.***#
Double Chain Silicates	***Amphibole***◊ Group (e.g., Hornblende)	50-60%	15-22% ‡	0-9% †	2 (120°-60°)  5½	~3.3 black	Found in ***Continental Crust***◊
Sheet Silicates	***Mica*** Group (e.g., ***Biotite***◊) (e.g., ***Muscovite***◊)	39% 39%	18-33% ‡ 0%	6% † 20%	***1*** *(perfect)*  2½	~3.0 black 2.8 slvr	Found in ***Continental Crust***◊
	Clay Group (e.g., Kaolinite)	46%	0%	21% †	***Microscopic platelets*** 	2.6 green or gray	From ***chemical weathering of silicates****
Frame-work Silicates	***Feldspar*** Group, Plagioclase(***Na***◊-***Ca***#) Orthoclase (***K***◊)	43-69% 76%	0% 0%	10-19% † 10% †	2 (90°)  6	2.6 wht-blk 2.7 pink	***Ca Plag.***# in ***<u>Oceanic Crust</u>*** ***Others Contin***◊.
	Quartz *(pure SiO_2◊)*	100%	0%	0%	***none*** (fracture)  7	2.6 white to gray	Concentrated in ***Continental*** Environments

General trends toward bottom: ***Increasing SiO_2, Decreasing Fe/Mg, Lighter in density, Lighter in Color***

\# Oceanic Crust is mostly Pyroxene and Ca-Feldspar → more dense and dark in colour.

◇ Continental Crust is mostly rich in silica and low Fe → less dense and lighter in colour.

Melting points and crystallization temperature decreases towards the bottom.

Melting points and crystallization temperature decreases towards the bottom.

Resistance to chemical weathering increases towards the bottom.

All silicate minerals are concerted to clay minerals by chemical weathering.

Use of Silicate Minerals

- Silicate minerals are a natural resource we can't live without on our planet, and not just because of our increasing reliance on computers.

- Without quartz, there would be no glass.

- Without the clay minerals, we would have no ceramics or pottery. We use silicate minerals in the manufacture of many building materials, including bricks and concrete.

- The weathering of silicate minerals on the surface of Earth produces the soils in which we grow our foods and the sand on our beaches.

Gemstones

See a brief list (Table 5.2) in the Marshak's book

- Gemstones are particularly rare and beautiful minerals. The gems or jewels found in jewelry have been faceted using a lap. The facets are not natural crystal faces or cleavage surfaces. The fire of a jewel comes from the way it reflects light internally.

- Not all gemstones ate minerals (Amber, pearl etc.)

Gemstones cannot change and/or alter your luck, mood, health, relationship status, job, promotion etc. and have no relationship with planetary system (there is also no Rahu and Ketu).

Next Lecture

Identification of Minerals
(and Intro to Rocks)

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 13. Identification of Minerals

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Physical properties of Minerals
- Identification methodology

Reference:
Chapter 3, Grotzinger_Jordan's Book
Chapter 5, Marshak's Book

Most images used in this presentation are from different web sources and a few are own collection

Minerals

- We learnt, there are more than 4000 minerals and they occur naturally.
- There are certain tools and techniques (qualitative, quantitative and relative), which help geologists to identify minerals easily and quickly.
- The quantitative identification techniques are mostly micro-scale and include power-XRD, EPMA, Optical Microscopy, Electron Microscopy (scanning and transmission) and many other spectroscopic tools.
- In the field, geologist rely on some basic physical properties of the minerals for identification. Of course, experience plays a major role. In other words, one has to see minerals, in reality.

The Physical Properties

LUSTRE

CLEAVAGE

COLOUR

STREAK

DENSITY

HARDNESS

OPTICAL PROPERTIES

CRYSTAL FORM

FRACTURE

MAGNETISM

ODOR

REACTIVE

COLOUR

Color is one of the most obvious properties of a mineral but it is often of limited diagnostic value, especially in minerals that are not opaque.

While many metallic and earthy minerals have distinctive colors, transucent or transparent minerals can vary widely in color.

Amethyst (purple)

Smoky Quartz (bworn-black)

Citrine Quartz (yellowish)

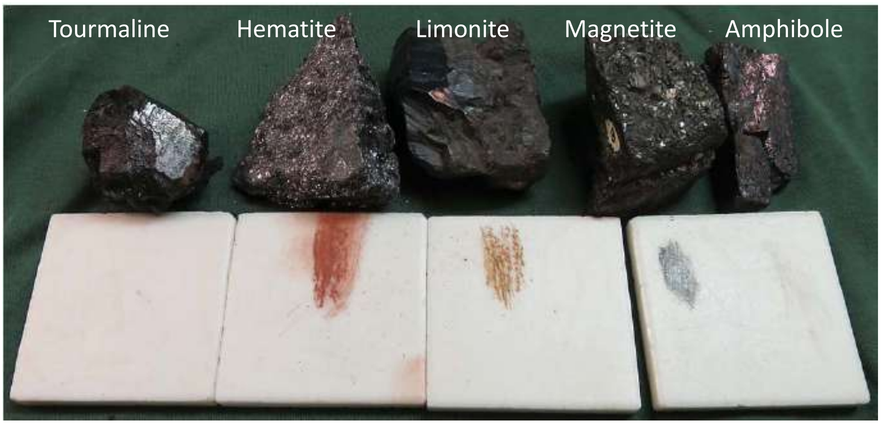
Rose Quartz (pink-reddish)

Quartz Crystal (colourless)

COLOUR

STREAK

The mineral-colour is seen when light reflects off the surface of the sample. The colour can be variable due to surface texture. A way to get around this problem is to grind a small amount of the sample to a powder and observe the colour of the powder. This colour is the mineral's **streak**. The mineral can be powdered by scraping the sample across a piece of unglazed porcelain called a **streak plate.**



LUSTRE

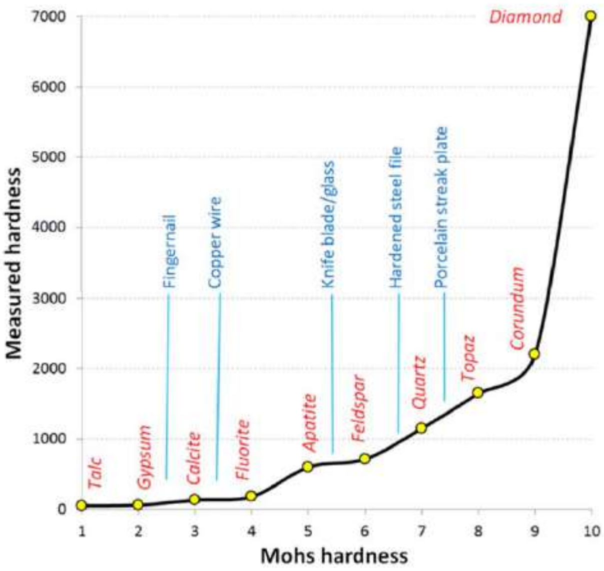
Lustre is the way light reflects off the surface of a mineral, and the degree to which it penetrates into the interior. The key distinction is between **metallic** and **non-metallic lustre**. If a non-metallic mineral has a shiny, reflective surface, it is said to have a **glassy** lustre. If the mineral surface is dull and non-reflective, it has an **earthy** lustre

Clockwise from the left: Metallic (galena); Metallic (pyrite); Vitreous (quartz); Waxy (chalcedony); Pearly (talc); and Earthy (goethite)

HARDNESS

One of the most important diagnostic properties of a mineral is its hardness. In practical terms, hardness determines whether or not a mineral can be scratched by a particular material.

In 1812 German mineralogist Friedrich Mohs came up with a list of 10 minerals representing a wide range of hardness, and numbered them 1 through 10 in order of increasing hardness.



CRYSTAL HABIT/SHAPE

When minerals form within rocks, there is a possibility that they will form in distinctive crystal shapes if they are not crowded out by other pre-existing minerals. Every mineral has one or more distinctive **crystal habits** determined by their atomic structure, although it is not that common in ordinary rocks for the shapes to be obvious.

Fibrous = fiber-like, similar to hair or cotton fibers. **Asbestos.**

Acicular = needle-shaped. **Natrolite; Kyanite**

Prismatic = prism-shaped. **Tourmaline**

Blocky = shaped like a block or brick. **Orthoclase**

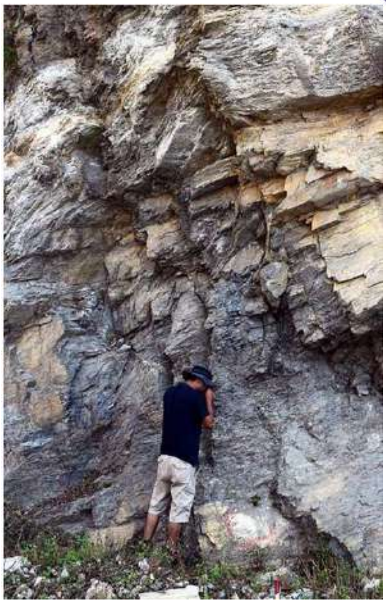
CRYSTAL HABIT/SHAPE

Equant approximately equal size in all directions.

Platy = plate-shaped, flat. **Biotite, Muscovite.**

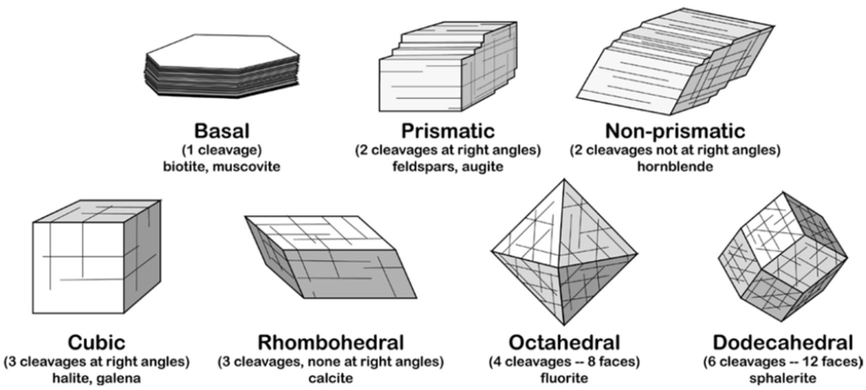
Massive = compact mass **Magnetite.**

Earthy = fine-grained with a dull, dirt-like appearance. **limonite.**

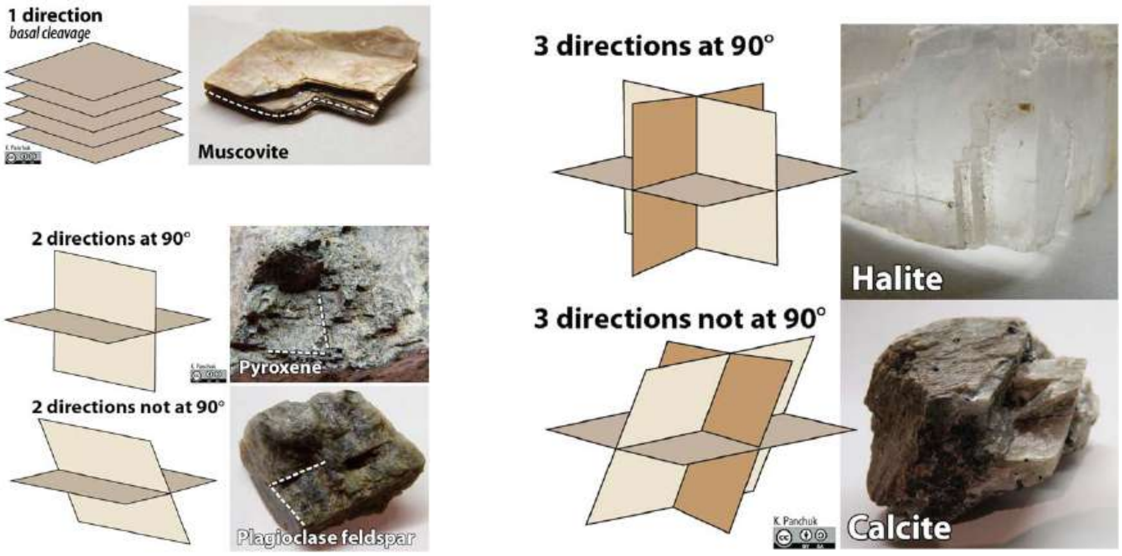


Mineral CLEAVAGES & FRACTURES

Cleavage and fracture describe how a mineral breaks. These are the most important diagnostic features of many minerals, and often the most difficult to understand and identify. **Cleavage** is what we see when a mineral breaks along a plane or planes, while **fracture** is an irregular break. Some minerals tend to cleave along planes at various fixed orientations. Some, do not cleave at all, only fracture. Minerals that have cleavage can also fracture along surfaces that are not parallel to their cleavage planes.



Mineral CLEAVAGES & FRACTURES



Mineral CLEAVAGES & FRACTURES

Fracture surfaces can cut a mineral grain in any direction. Fractures are generally rough or irregular, rather than flat, and thus appear duller than cleavage surfaces. Some minerals fracture in a way that helps to identify them. For example, quartz has no cleavage but, like glass, it breaks along numerous small, smooth, curved surfaces called conchoidal fractures

Density

Density is a measure of the mass of a mineral per unit volume, and it is a useful diagnostic tool in some cases.

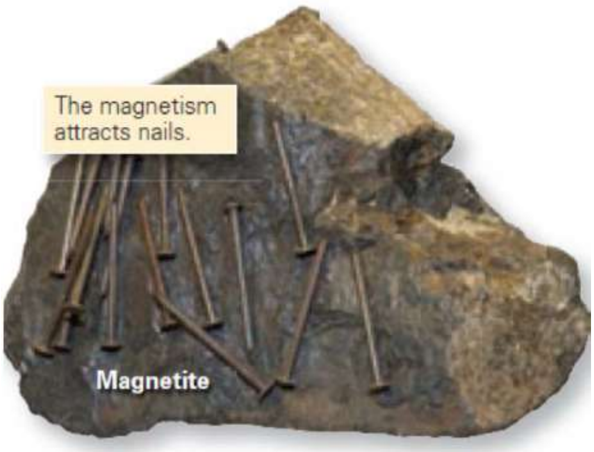
Most common minerals, such as quartz, feldspar, calcite, amphibole, and mica, are of average density (2.6 to 3.0 g/cm^3), and it would be difficult to tell them apart on the basis of their density. On the other hand, many of the metallic minerals, such as pyrite, hematite, and magnetite, have densities over 5 g/cm^3. If you picked up a sample of one of these minerals, it would feel much heavier compared to a similarly sized sample of a mineral with average density.

A limitation of using density as a diagnostic tool is that one cannot assess it in minerals that are a small part of a rock with other minerals in it. But, one can measure precisely the density in the laboratory.

Magnetism

Some minerals are attracted to a hand magnet. To test a mineral for magnetism, just put the magnet and mineral together and see if they are attracted.

Magnetite is the only common mineral that is always strongly magnetic.



Reaction with Acid

Some minerals, especially carbonate minerals, react visibly with acid. (Usually, a dilute hydrochloric acid [HCl] is used.)

When a drop of dilute hydrochloric acid is placed on calcite, it readily bubbles or effervesces, releasing carbon dioxide.

Taste, Odor, Feel

Some minerals have a distinctive taste (halite is salt, and tastes like it).

some a distinctive odor (the powder of some sulfide minerals, such as sphalerite, a zinc sulfide, smells like rotten eggs).

Soaking clay minerals with water gives an earthy-smell.

Some with a distinctive feel (talc feels slippery).

Next Lecture

Introduction to Rocks

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 14. Rocks

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Definition and Characteristics
- Rock Cycle and Plate Tectonics
- Driving force(s) of Rock Cycles
- Major rock types, their genesis and involvement in Rock Cycles

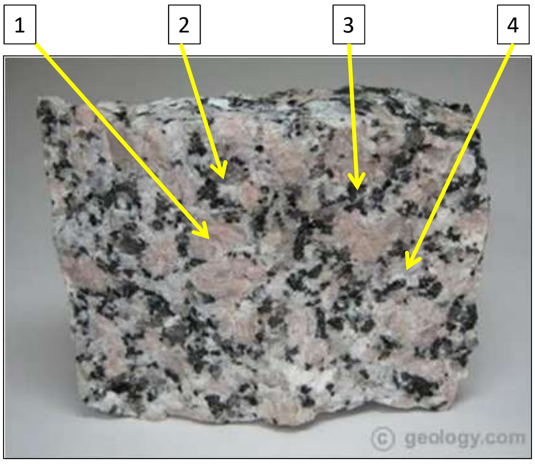
Reference (selective reading):
Chapter 4-6, Grotzinger_Jordan's Book
Chapter 5-8, Marshak's Book

Basics

Basics

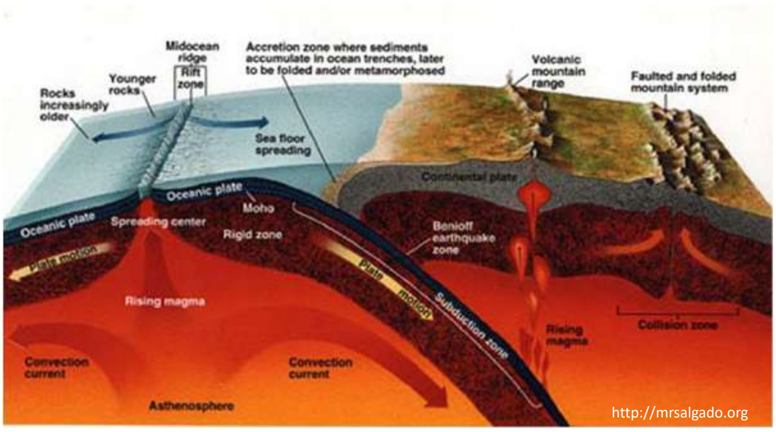
- Rock is a naturally occurring solid mixture of one or more minerals that may also include organic matter.
- Most of the rocks is made of crystalline minerals, but there are exceptions.
- Rocks are always changing through time.
- Natural processes make and destroy rocks. They change each type of rock into other types of rock and shape Earth’s features.
- Different natural processes influence the type of rock that is found in each area of Earth’s surface

Basics



Creation and destruction of lithosphere

- Plate tectonics and continent building
  - Accretion through collisions
  - Recycling of material
  - Subduction
  - Segregation of melts



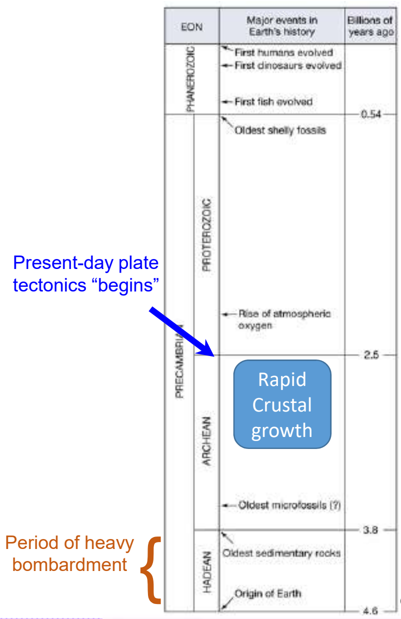
Evolution of modern plate tectonics

- Presence moderate temperatures

- Heat removal from mantle through subduction of cool oceanic lithosphere and upwelling of new crust
  - Drives convection cells
  - Allows basalt eclogite transition to be shallow
  - Subduction leads to fractional melting of oceanic crust and segregation to form continental crust

- Presence of water
  - Needed for granite formation
  - Catalyzes fractional melting in subducting sediments

Modern plate tectonics



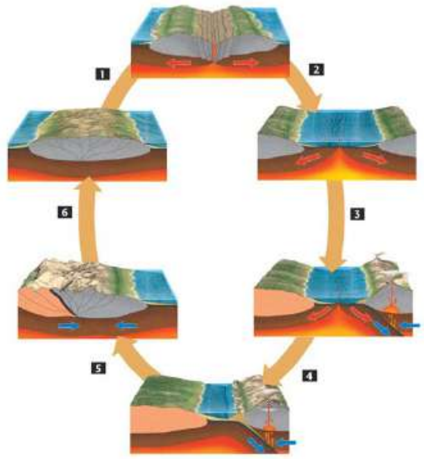
- Early plates became bigger and thicker

- Continued recycling of oceanic crust formed large amounts of buoyant continental crust
  - Continued partial melting/distillation
  - Separation of Si and other elements from Mg and Fe

- Decrease in heat production slowed mantle convection
  - Drove system to larger convection cells
  - Allowed larger plates to travel farther on the Earth’s surface and cool more
  - Led to subduction rather than collision of plates
  - Modern plate tectonics

Since the Archaean

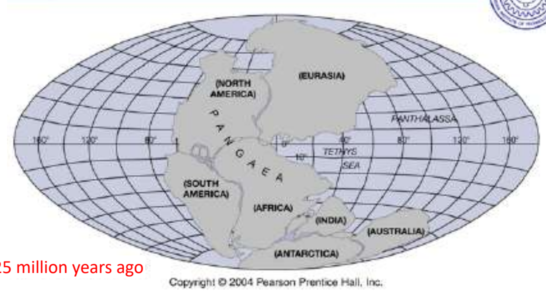
- Intensity of plate tectonics has varied over time
- Wilson cycles – 500 my cycles
  - Evidence of supercontinent 600-900 mybp
  - Pangea formed ~ 300 mybp
  - Causes not well understood



- Periods of rapid sea floor spreading (and vice versa)
  - Sea level rises because large amounts of shallow basalt form and don't cool (and subside) much
  - High CO_2 release – released at spreading centers when new crust forms and subducting crust has sediment on it including calcite which releases CO_2 when it melts

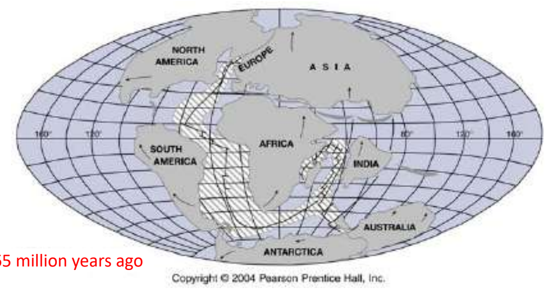
Age of crustal material

- Continental crust is older because it doesn't get subducted
  - Too buoyant
  - Becomes "core" for accretion
  - Collisions (closing of basins) mediate accretion
  - Losses only from weathering and subduction of sediment
  - Oldest rocks are 4.3 – 4.4 by old



225 million years ago

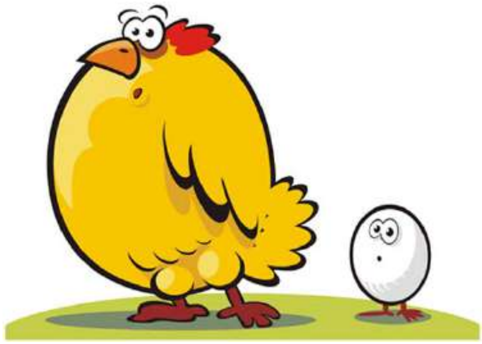
- Oceanic crust is young and constantly recycled (and fractionated)
  - Oldest oceanic crust is furthest from spreading centers near subduction zones



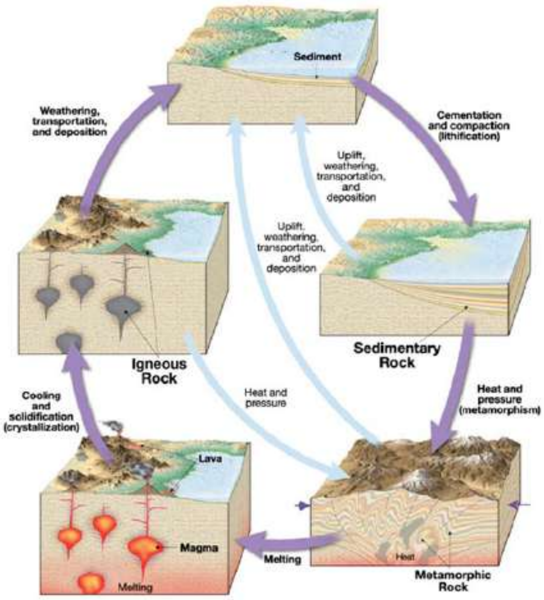
65 million years ago

Coming back to Rocks ….

- Plate tectonics certainly plays a major role in regulating the Rocks on the surface of the earth.
- And… we did not have rocks and plate tectonics since the beginning of the Earth..
- **The chicken egg problem**: which started first – rock cycle or plate tectonics?



The Rock Cycle



Igneous Rocks

Rocks that form by the freezing or solidification of melt

Sedimentary Rocks

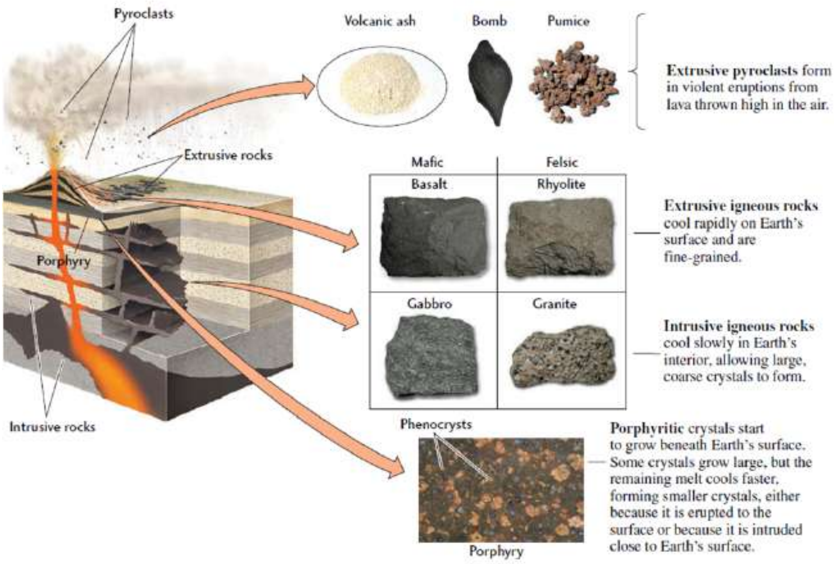
Rocks that form by the cementing of grains or fragments of pre-existing rocks, or by the precipitation of minerals out of a solution

Metamorphic Rocks

Rocks that form when pre-existing rocks change due to temperature or pressure, and/or as a result of squashing or shearing (deformation).

What was the first rock?

Igneous Rocks



MAGMA

Molten Rock

Usually with dissolved gasses

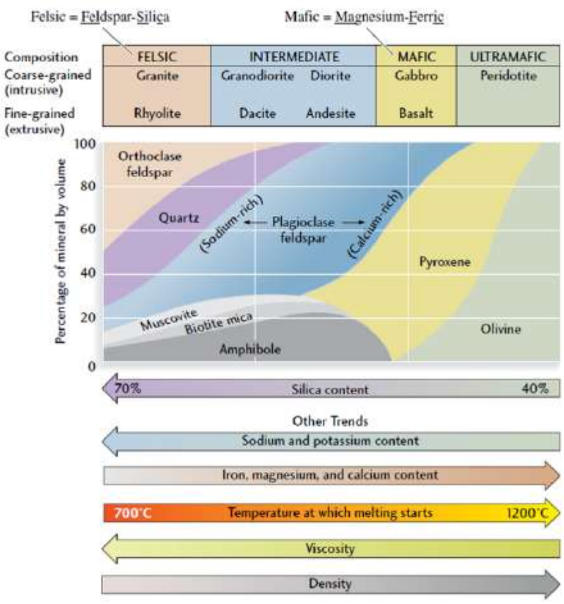
Generated at depth

Eruptions if magma (lava) reaches surface

If doesn't reach surface, Solidifies underground

- Intrudes *country or host rock*
- Intrusive *contact*
- *Xenolith- 'foreign body'*

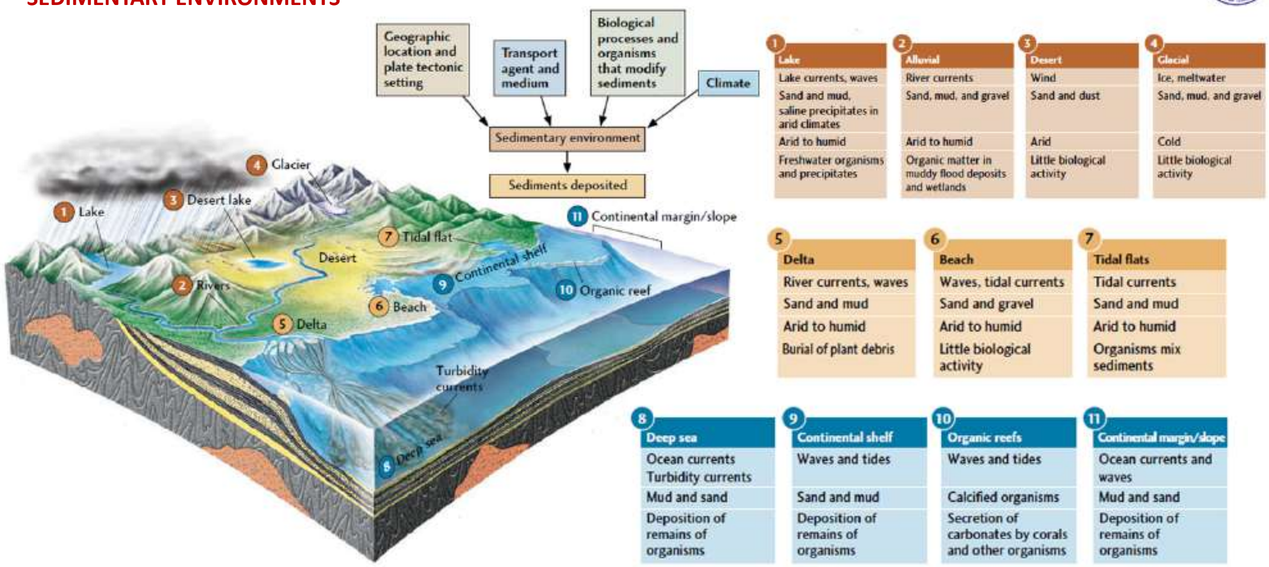
Igneous Rocks



Classification model for igneous rocks. The vertical axis shows the minerals contained in a given rock as a percentage of its volume. The horizontal axis shows the silica content of a given rock as a percentage of its weight. Thus, if you knew by chemical analysis that a coarsely textured rock sample was about 70% silica, you could deduce that its composition was about 6% amphibole, 3% biotite, 5% muscovite, 14% plagioclase feldspar, 22% quartz, and 50% orthoclase feldspar. Your rock would be granite. Although rhyolite has the same mineral composition, its fi ne texture would eliminate it from consideration.

Sedimentary Rocks

SEDIMENTARY ENVIRONMENTS



Sedimentary Rocks

Texture	Sediment Name and Particle Size	DETRITAL ROCKS Comments	Rock Name
Clastic	Gravel (>2 mm)	Rounded rock fragments	Conglomerate
		Angular rock fragments	Breccia
	Sand (1/16–2 mm)	Quartz predominates	Quartz sandstone
		Quartz with considerable feldspar	Arkose
		Dark color; quartz with considerable feldspar, clay, and rocky fragments	Graywacke
	Mud (<1/16 mm)	Splits into thin layers Breaks into clumps or blocks	Shale Mudstone
Group	**Texture**	**CHEMICAL ROCKS Composition**	**Rock Name**
Inorganic	Clastic or nonclastic	Calcite, $CaCO_3$	Limestone
	Nonclastic	Dolomite, $CaMg(CO_3)_2$	Dolostone
	Nonclastic	Microcrystalline quartz, SiO_2	Chert
	Nonclastic	Halite, NaCl	Rock salt
	Nonclastic	Gypsum, $CaSO_4 \cdot 2H_2O$	Rock gypsum
Biochemical	Clastic or nonclastic	Calcite, $CaCO_3$	Limestone
	Nonclastic	Microcrystalline quartz, SiO_2	Chert
	Nonclastic	Altered plant remains	Coal

Metamorphic Rocks

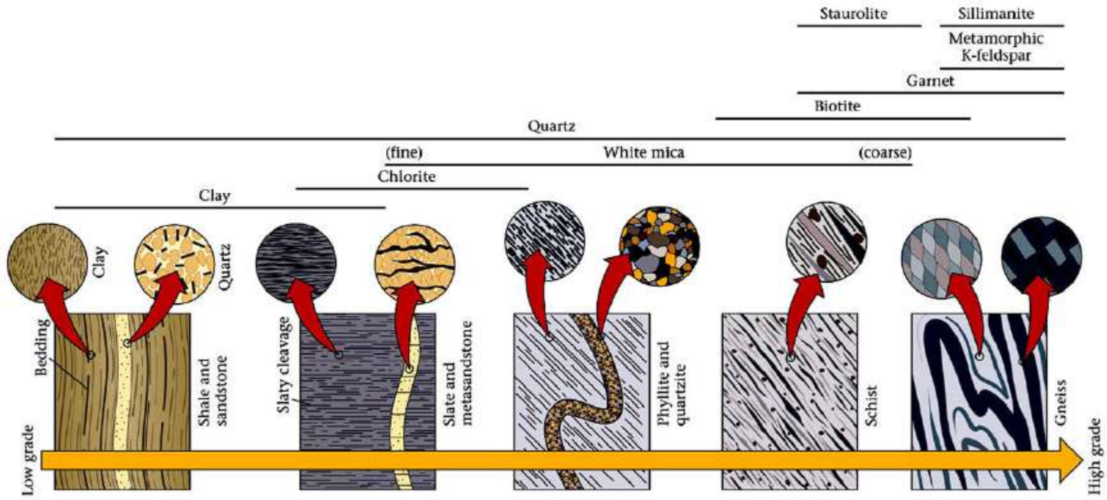
Metamorphic Textures – grains are interlocked and grew in place. Many different types of metamorphic textures.

Metamorphic Minerals – Certain minerals only grow under metamorphic temperatures and pressures. Called a **metamorphic mineral assemblage, or metamorphic facies.**

Foliation – The alignment of platy minerals or alternating layers of light (felsic) and dark (mafic) minerals.

Metamorphic Rocks

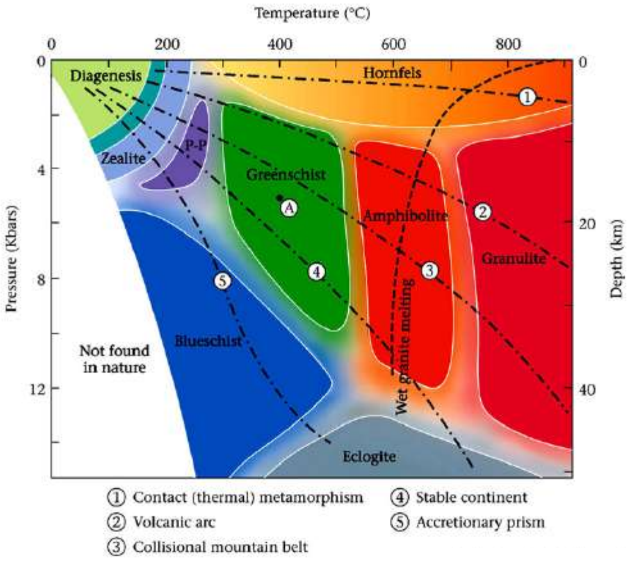
A single protolith (shale shown below) can form a variety of metamorphic rocks depending on the grade of metamorphism incurred after burial. Certain mineral assemblages reflect the grade of metamorphism



Metamorphic Rocks

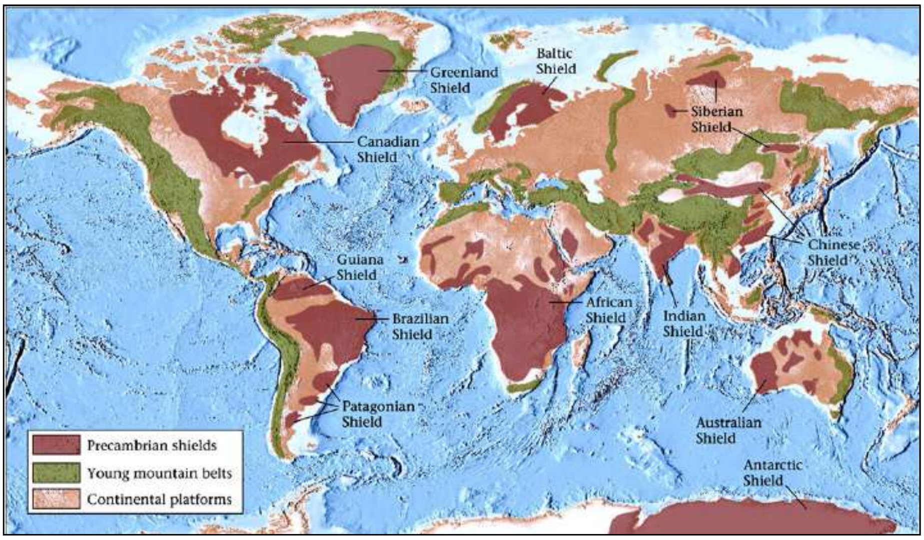
A given P-T horizon has a characteristic set of minerals that form. Which ones form depend on protolith composition

If you know the P-T conditions and the protolith composition, you can predict the mineralogy of the resultant metamorphic rock

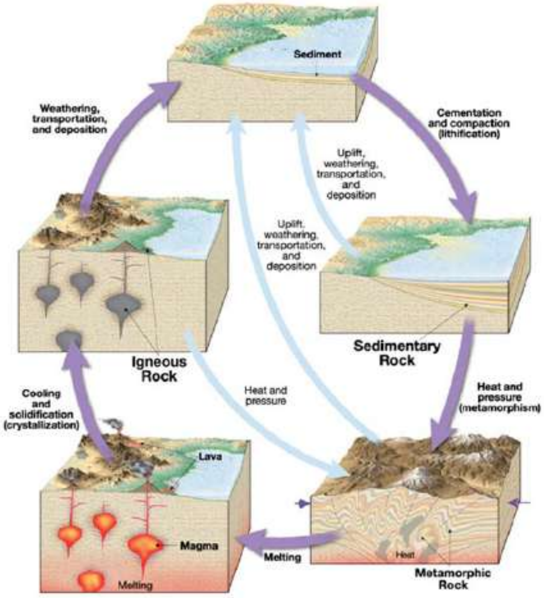


Metamorphic Rocks

- Where are the Metamorphic Rocks exposed today?



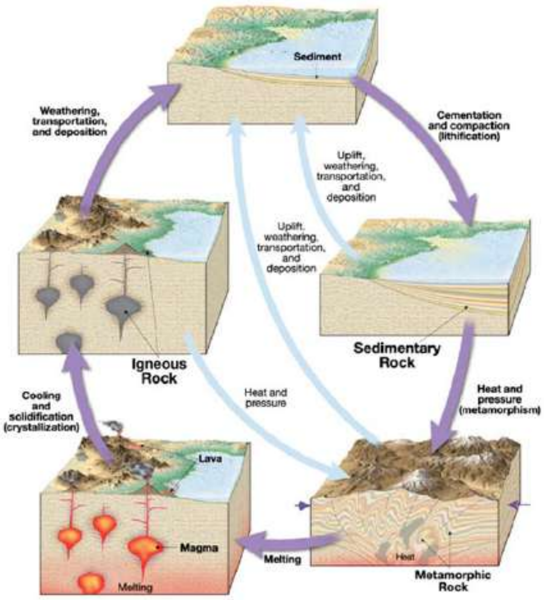
Let’s look this slide back again….



Processed involved in Rock Cycles

- Melting
- Cooling and solidification
- Weathering, transportation and deposition
- Cementation and compaction
- Heat and Pressure (subduction)
- Uplift

Let’s look this slide back again….



Processed involved in Rock Cycles

- Melting
- Cooling and solidification
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- Cementation and compaction
- Heat and Pressure (subduction)
- Uplift

Melting - I

MAGMA

- The tectonic plates don't really float on a liquid asthenosphere, rather the asthenosphere is a ductile solid and is only melted in specific locations.

- Most magma/lava is not 100% liquid.
  - Magma/Lava is made of many compounds, all of which have different melting temperatures.
  - Only a few percent of liquid is required to make a melt.

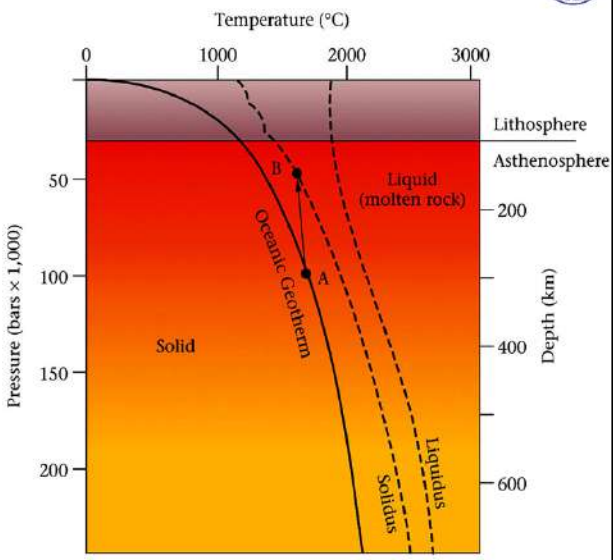
- Other than a rise in temperature, melting can happen because of:
  - Decrease in pressure (decompression)
  - Addition of volatiles (H_2O, CO_2, etc…)
  - Heat transfer from rising magma

Decompression Melting

- The Earth gets hotter with increasing depth due to primordial heat and radioactive decay of elements near the core.
- The rate at which temperature increases with depth is called the ***geothermal gradient***, or ***geotherm***
- Liquids have no organized structure, so to melt a rock, the mineral bonds must be broken
- At depth, confining pressure prevents atoms from breaking free of crystals

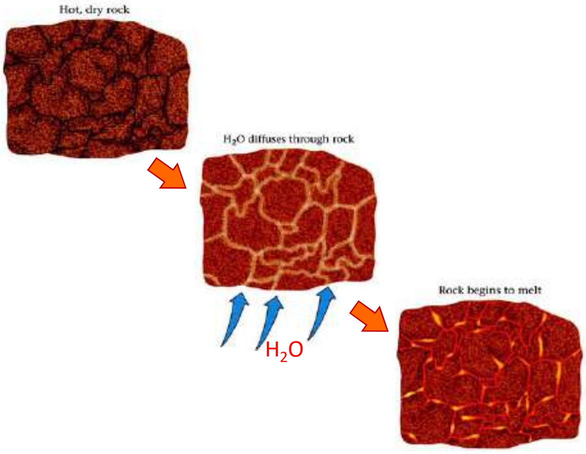
  Solidus: The temperature when a rock first begins to melt

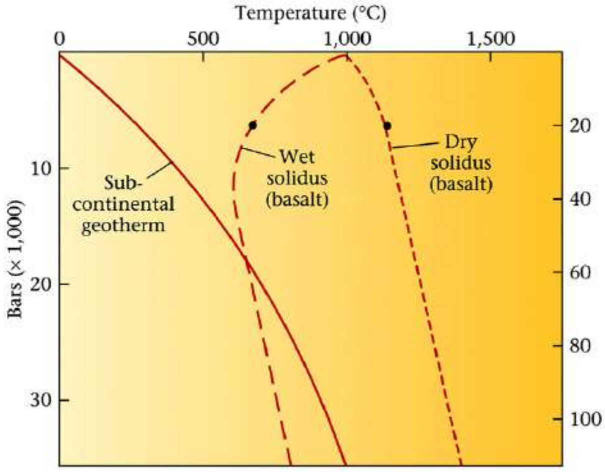
  Liquidus: The temperature where the last solid particle melts
- The asthenosphere cools only slightly as it rises (convection) because it is a good insulator (high specific heat)



Volatile induced melting

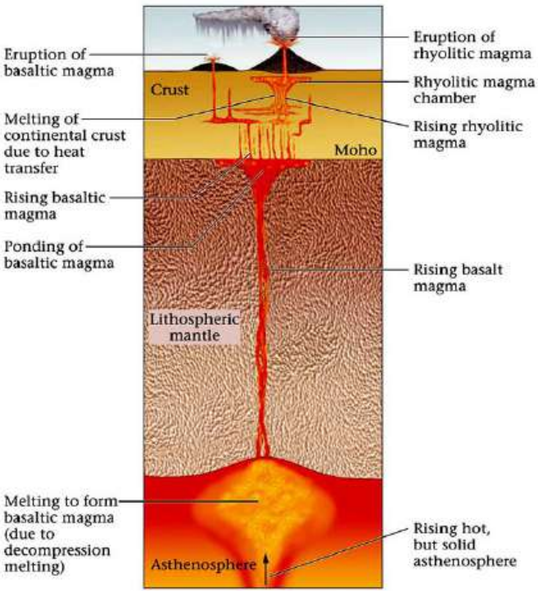
- Volatiles: A substance that can easily change into a gas at relatively low temperatures (H_2O, CO_2, etc…).
- The addition of volatiles at depth (mainly H_2O) seeps into rocks and helps break bonds (aids in melting).





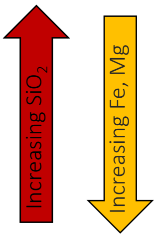
Melting due to Heat Transfer

- Melting can also occur when rising bodies of hot material essentially bake the nearby rock



Magma

- All magmas contain **Si** and **O**
  - Upon cooling, bond together into ***silicon-oxygen tetrahedrons;*** More silica (i.e. felsic), more viscous
  - Also contain varying amounts of other elements like Na, K, Al, Ca, Mg, Fe, etc…
- Dry magmas – no volatiles
- Wet Magmas – up to 15% volatiles
- Volatile content strongly effects the viscosity (ability to flow)
  - More volatiles, less viscous (easier to flow or more fluid)



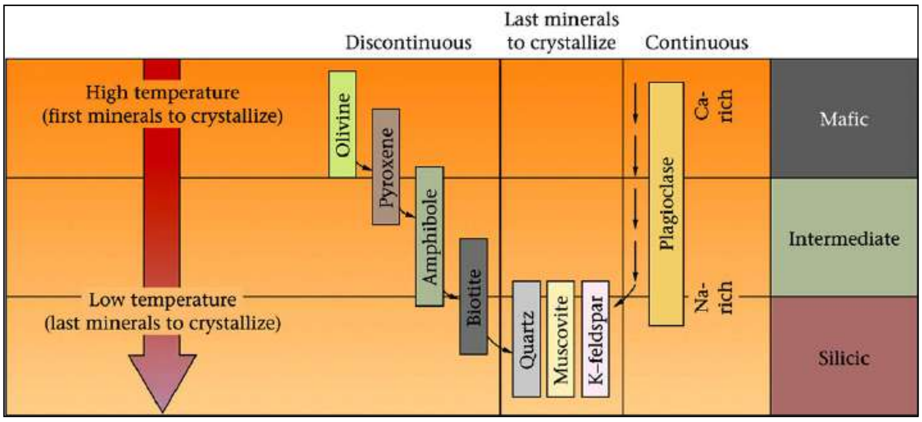
- Like rocks, not all magma is made of the same stuff
- We divide magmas into groups by their composition
  - **Felsic (Silicic):** 66-76% Silica (SiO_2)
    - Most viscous, Least dense (~2.5 gm/cm^3), melting point 650-800ºC
  - **Intermediate:** 52-66% SiO_2
  - **Mafic:** 45-52% SiO_2, lots of MgO, FeO, and Fe_2O_3
  - **Ultramafic:** 38-45% SiO_2, abundant MgO, FeO, and Fe_2O_3
    - Least viscous, Most dense (~3.5 gm/cm^3), melting point up to 1300ºC

Magma - volcanos

Type	Density	Temperature	Viscosity
Felsic	Very low	Very low (600 to 850°C)	Very High: Explosive eruptions.
Intermediate	Low	Low	High: Explosive eruptions.
Mafic	High	High	Low: Thin, hot runny eruptions.
Ultramafic	Very high	Very high (up to 1,300°C)	Very low

Bowen's Reaction series – Cooling and Crystallization

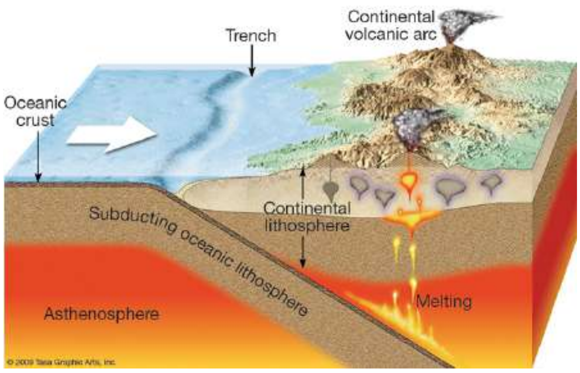
- In order to understand the melting and solidifying of magma we need to understand Bowen's reaction series. – *Bowen figured this out by melting rocks in an oven, letting them cool, and watching what minerals crystallized*
- This series outlines the order in which minerals form in a cooling melt
- Also applies in reverse order to rocks that are partially melted

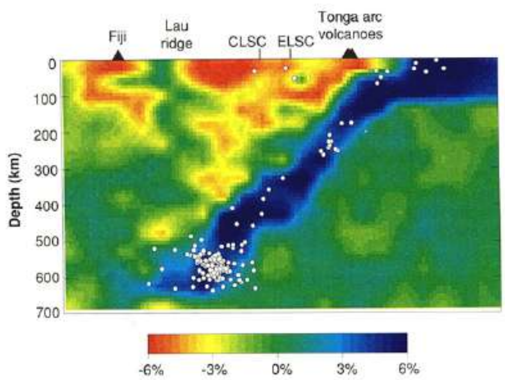


Discontinuous series (different minerals form) and Continuous series (Plagioclase only)

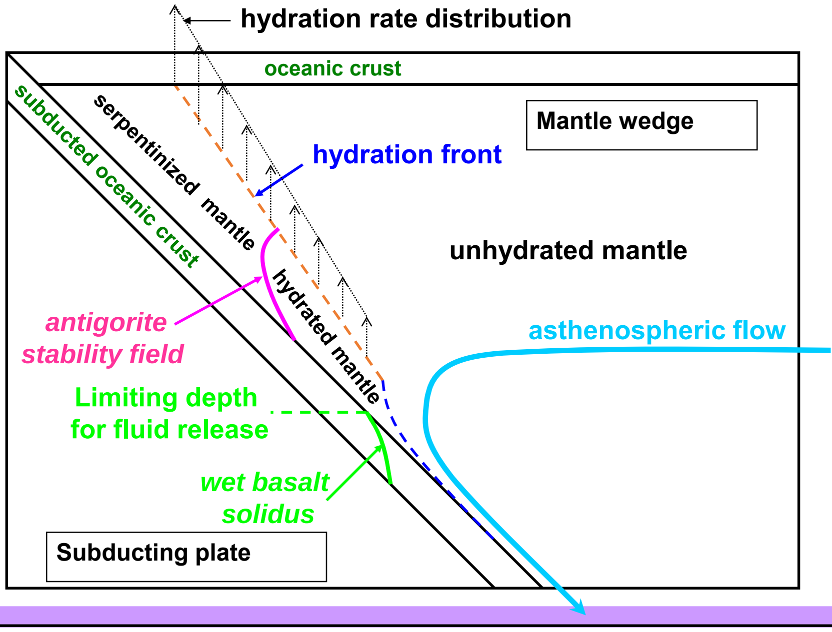
So, a melt gets less mafic as it cools; In heating, the first minerals to melt are felsic.

Subduction (heat and pressure)

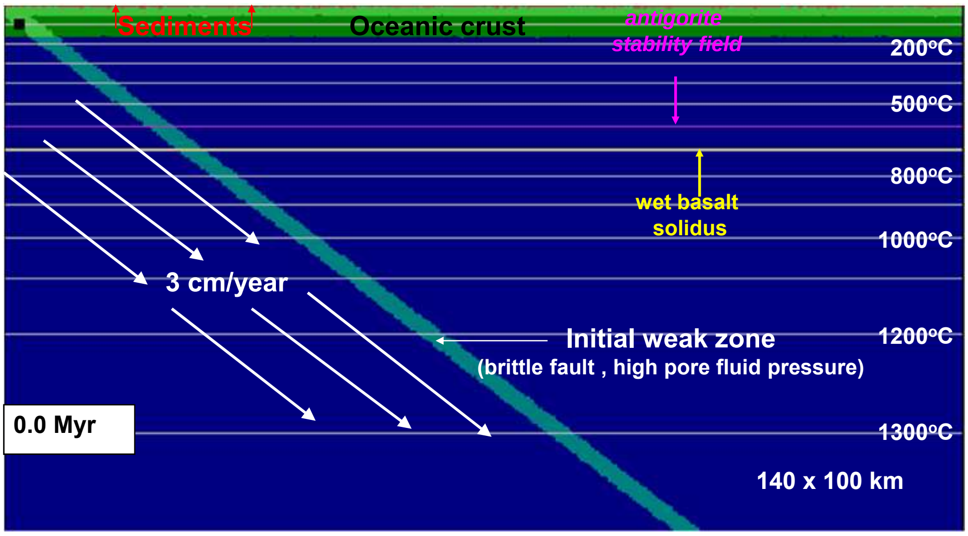




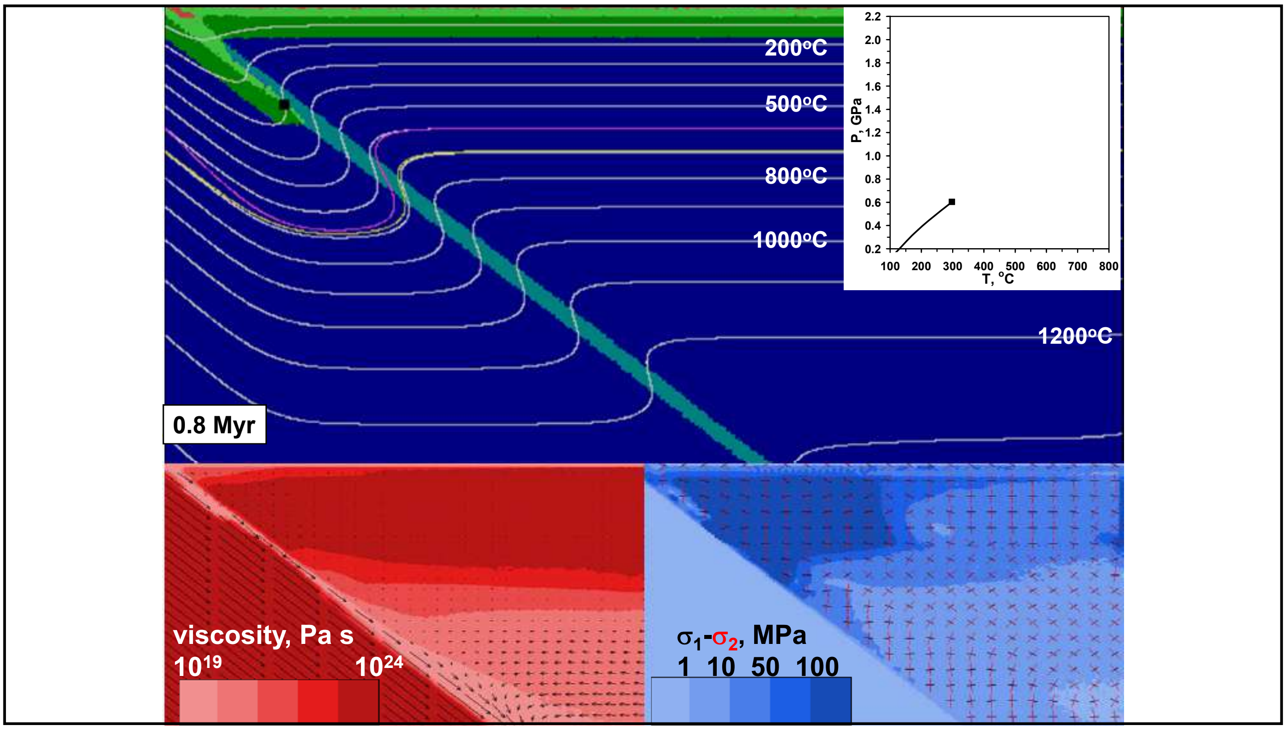
Subduction & Exhumation

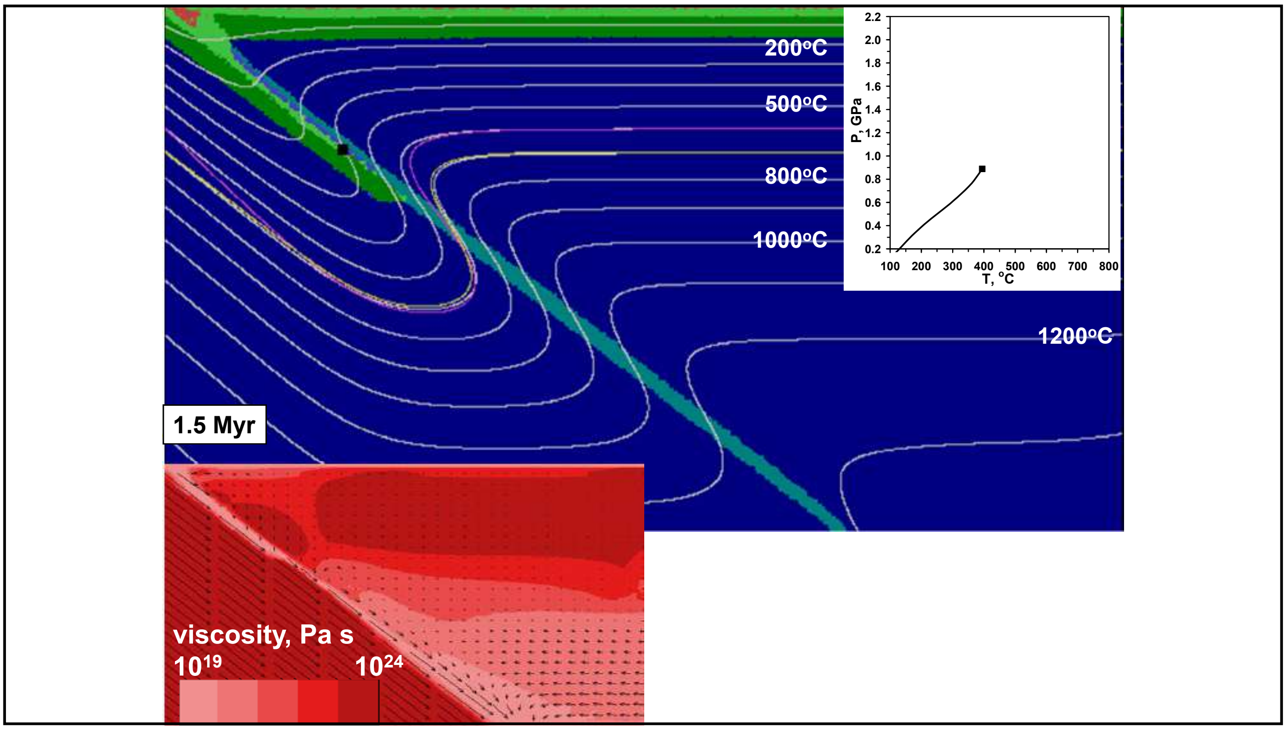


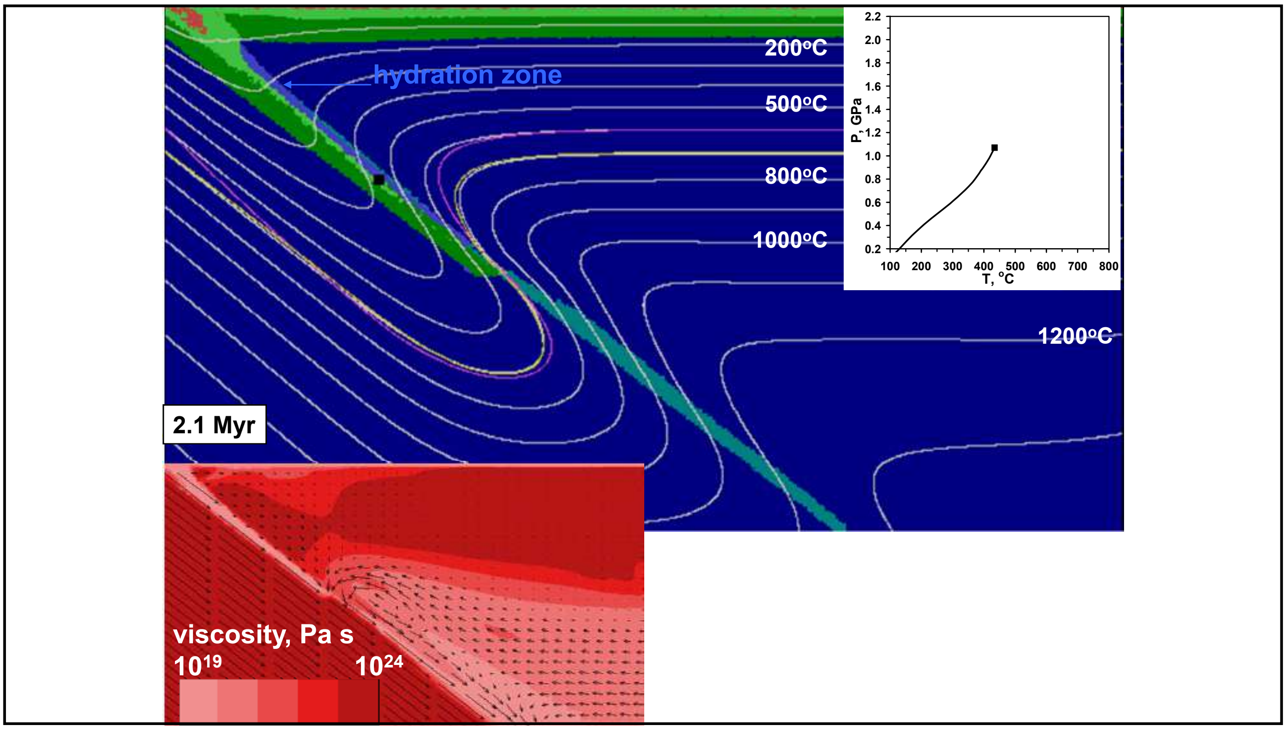
Subduction – Heat and pressure



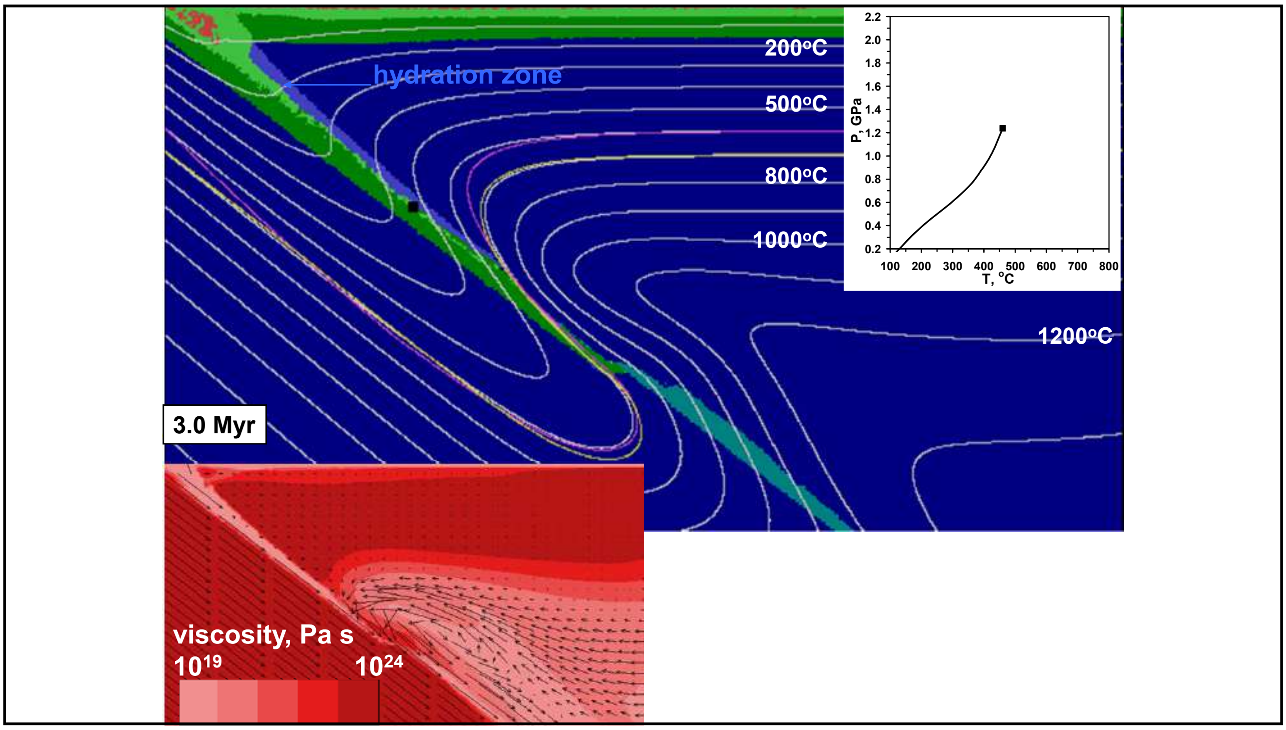
Litosphere: 40 Myr old; **Subduction:** rate 3 cm/year, angle 45°
Hydration of hanging wall: max rate 2 mm/year, max depth 90 km


200°C
500°C
800°C
1000°C
1200°C
0.8 Myr
P, GPa
T, °C
viscosity, Pa s
10^{19}
10^{24}
σ_1-σ_2, MPa
1 10 50 100

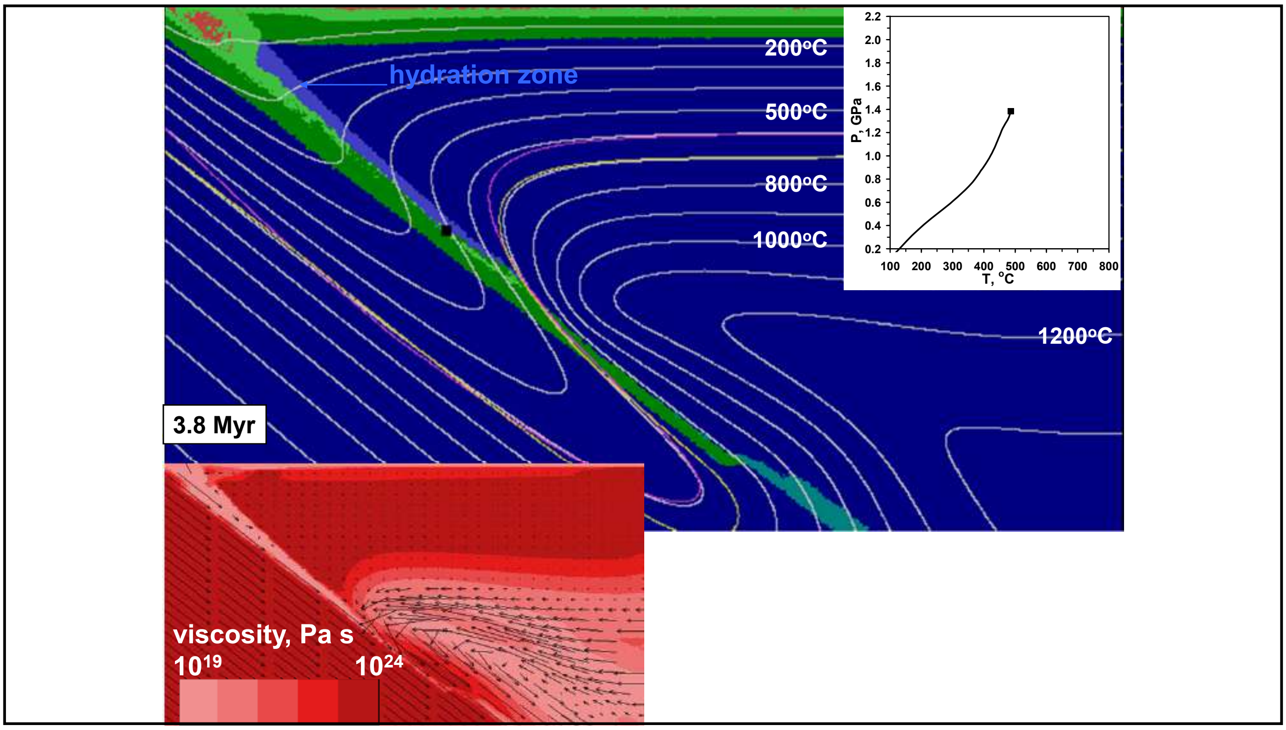

200°C
500°C
800°C
1000°C
1200°C
1.5 Myr
P, GPa
T, °C
viscosity, Pa s
10^{19}
10^{24}

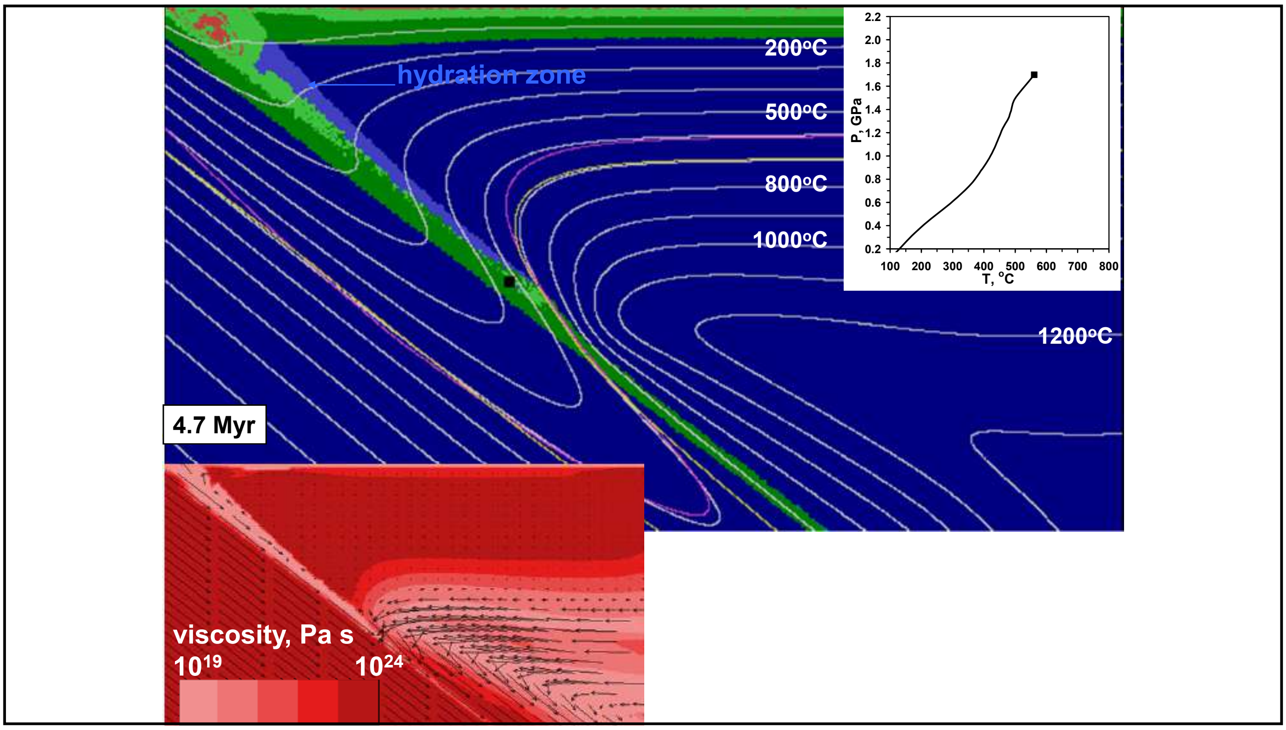


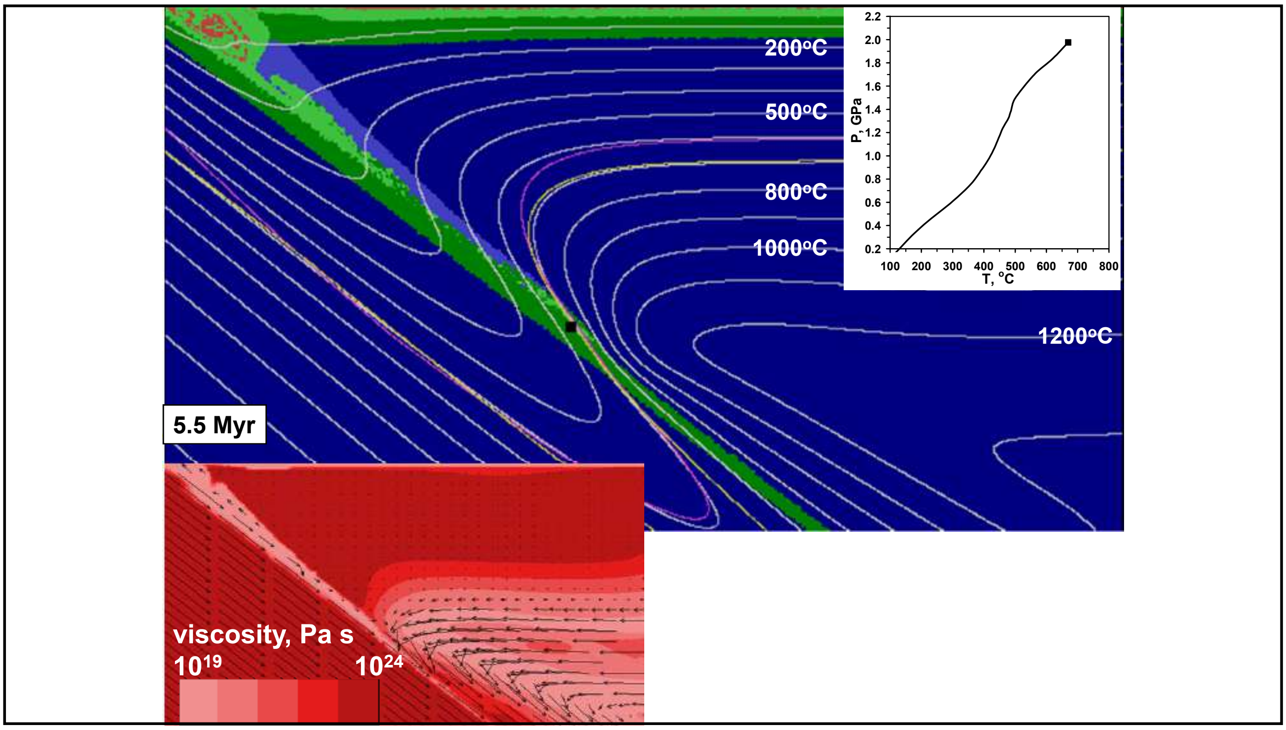
200°C
hydration zone
500°C
800°C
1000°C
1200°C
2.1 Myr
viscosity, Pa s
10^{19}
10^{24}
P, GPa
T, °C

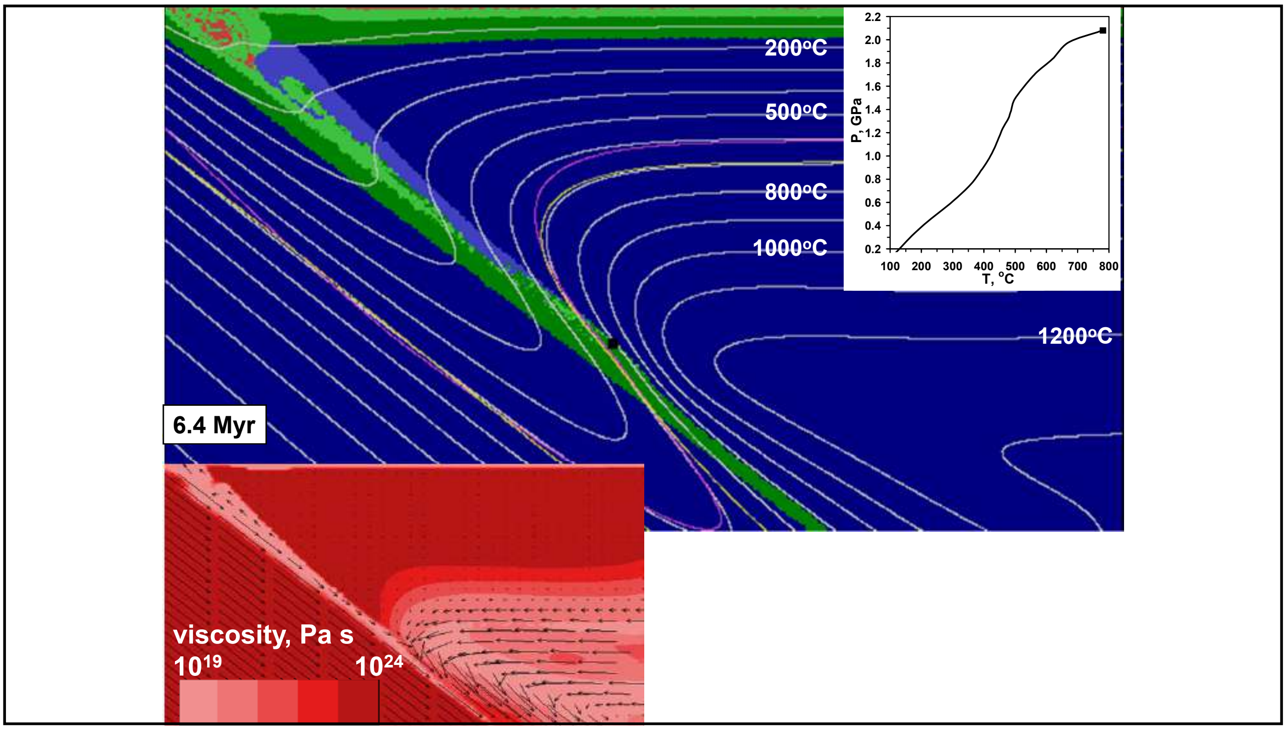


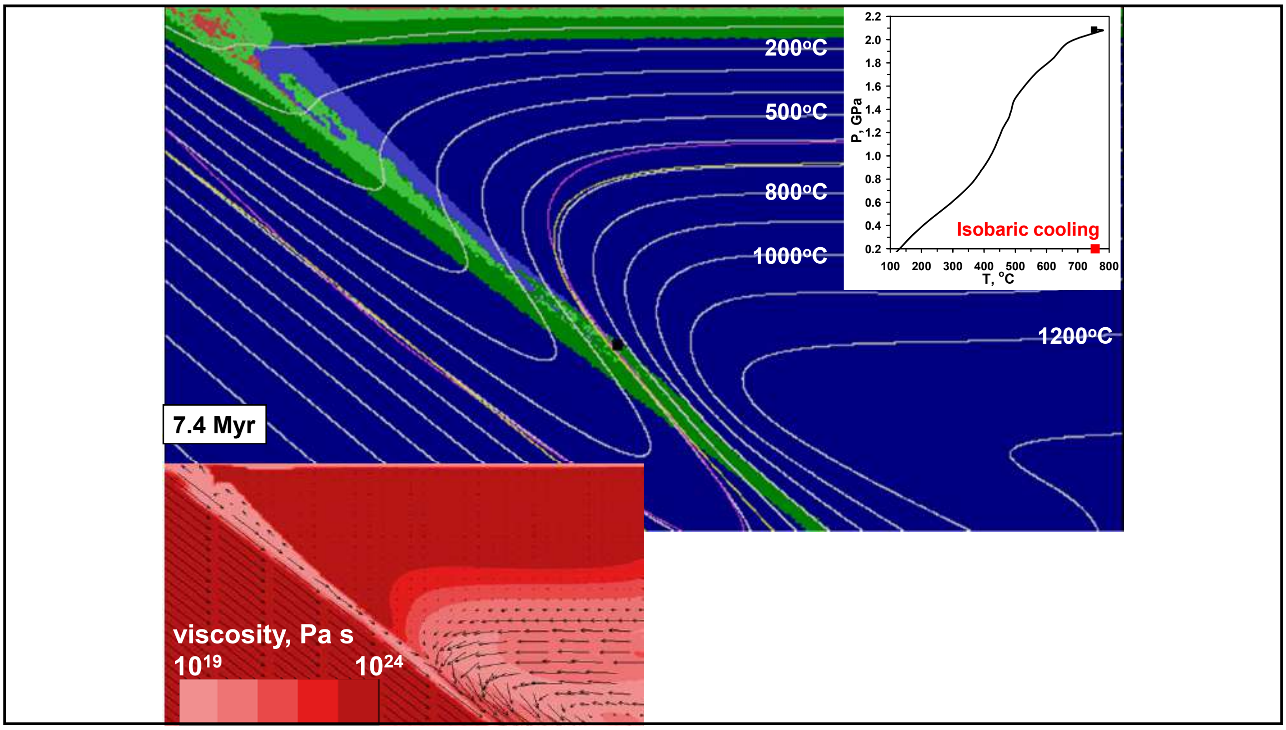
200°C
hydration zone
500°C
800°C
1000°C
1200°C
3.0 Myr
viscosity, Pa s
10^{19}
10^{24}
P, GPa
T, °C

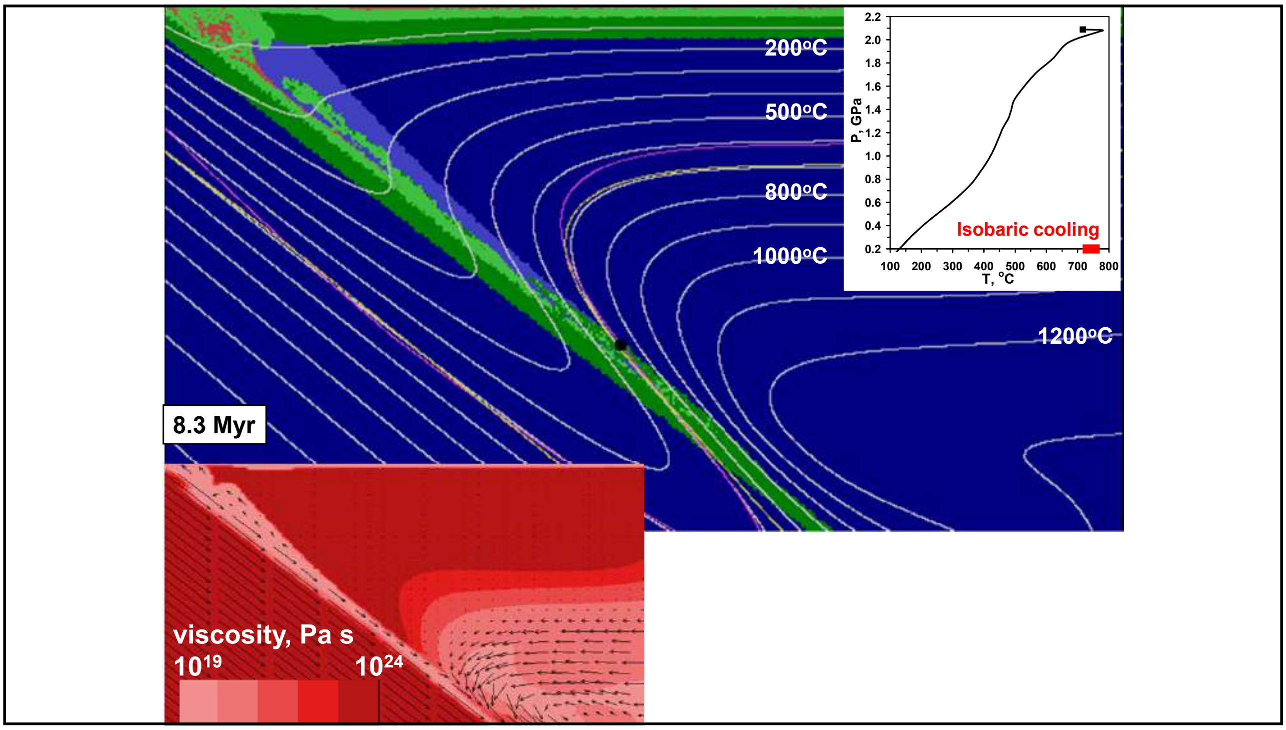

200°C
hydration zone
500°C
800°C
1000°C
1200°C
3.8 Myr
viscosity, Pa s
10^{19}
10^{24}
P, GPa
T, °C

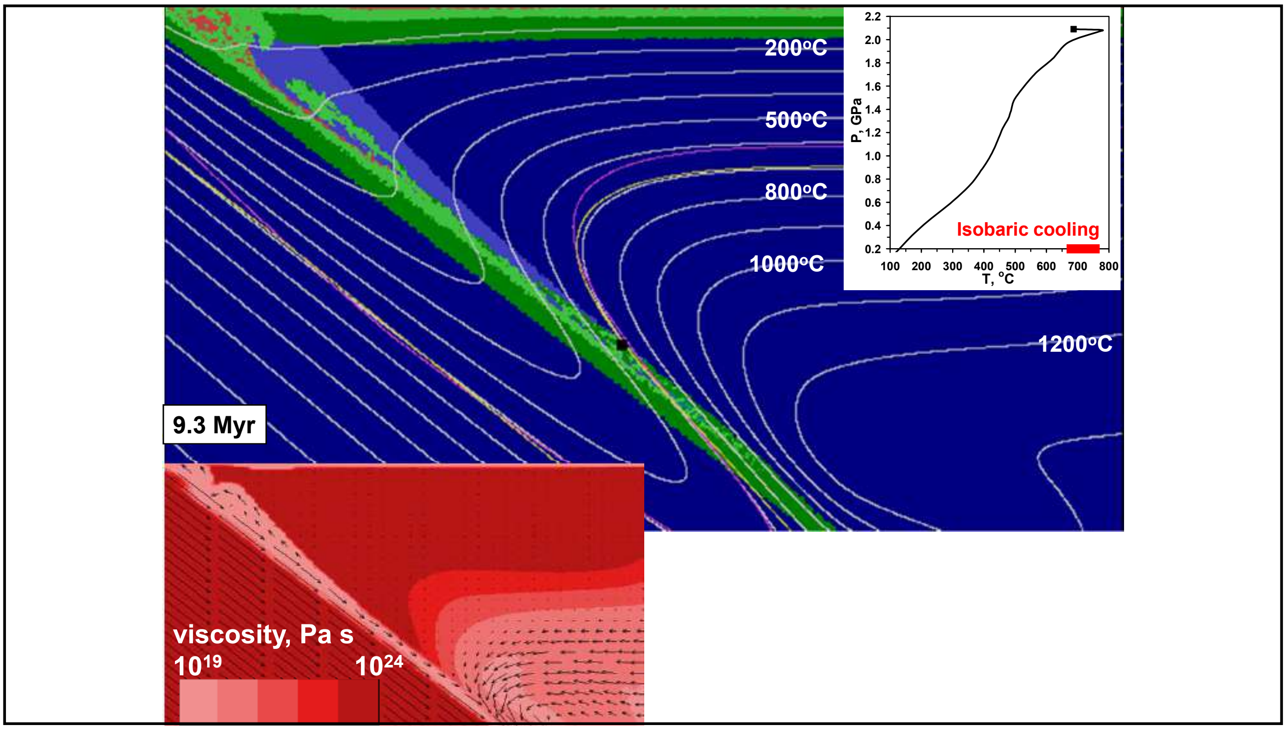

200°C
hydration zone
500°C
800°C
1000°C
1200°C
4.7 Myr
viscosity, Pa s
10^{19}
10^{24}
P, GPa
T, °C

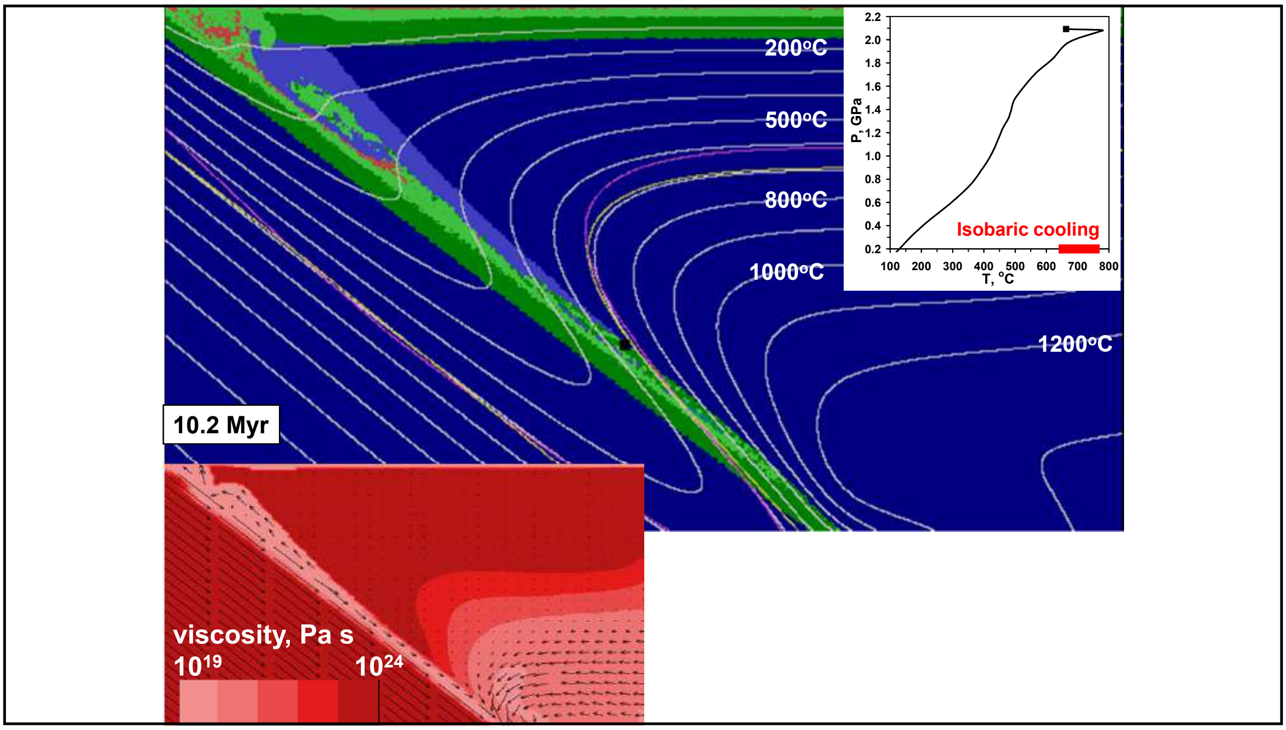

200°C
500°C
800°C
1000°C
1200°C
5.5 Myr
viscosity, Pa s
10^19
10^24
P, GPa
T, °C

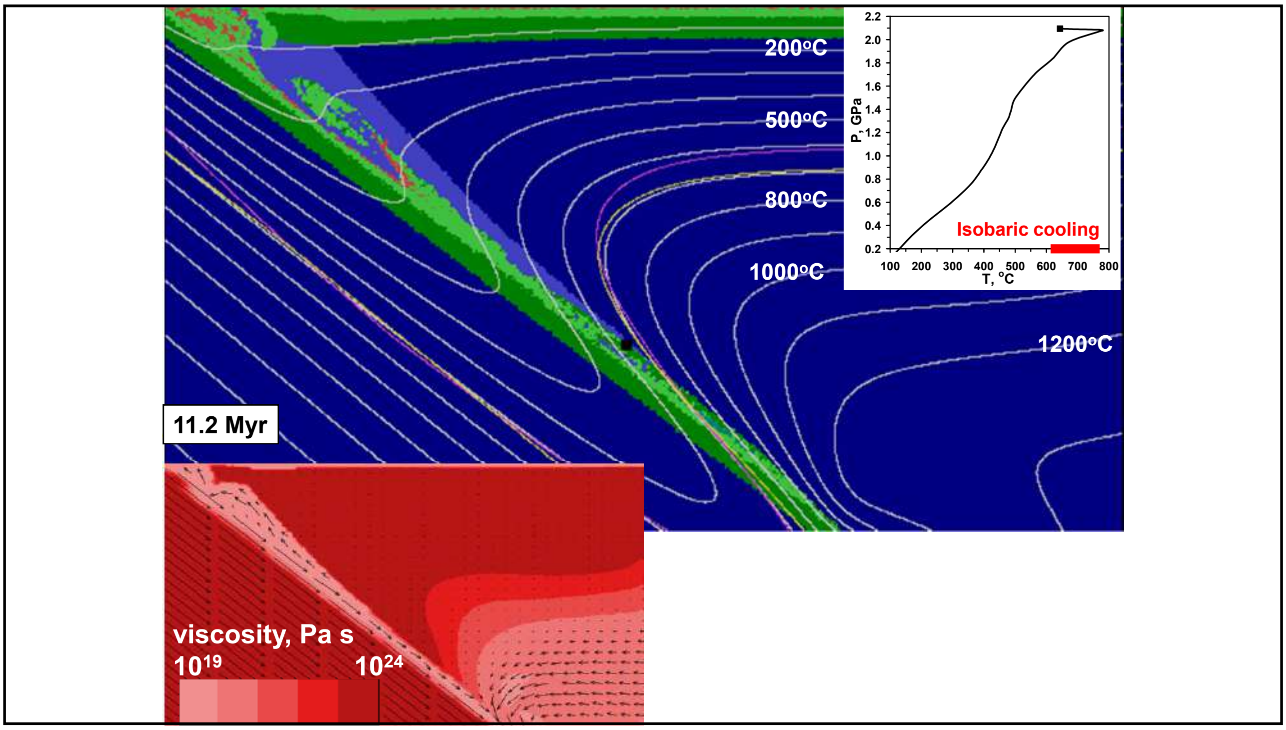

200°C
500°C
800°C
1000°C
1200°C
6.4 Myr
viscosity, Pa s
10^19
10^24
P, GPa
T, °C

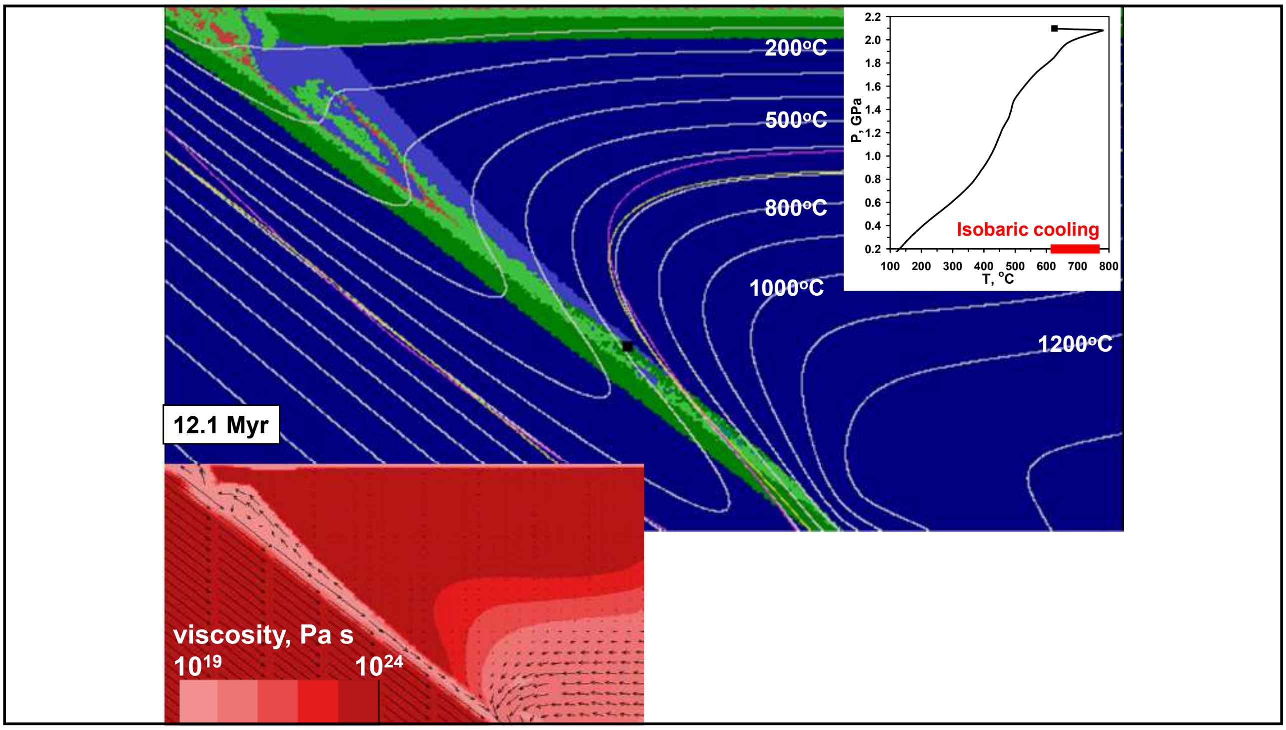

200°C
500°C
800°C
1000°C
1200°C
7.4 Myr
P, GPa
T, °C
Isobaric cooling
viscosity, Pa s
10^19
10^24

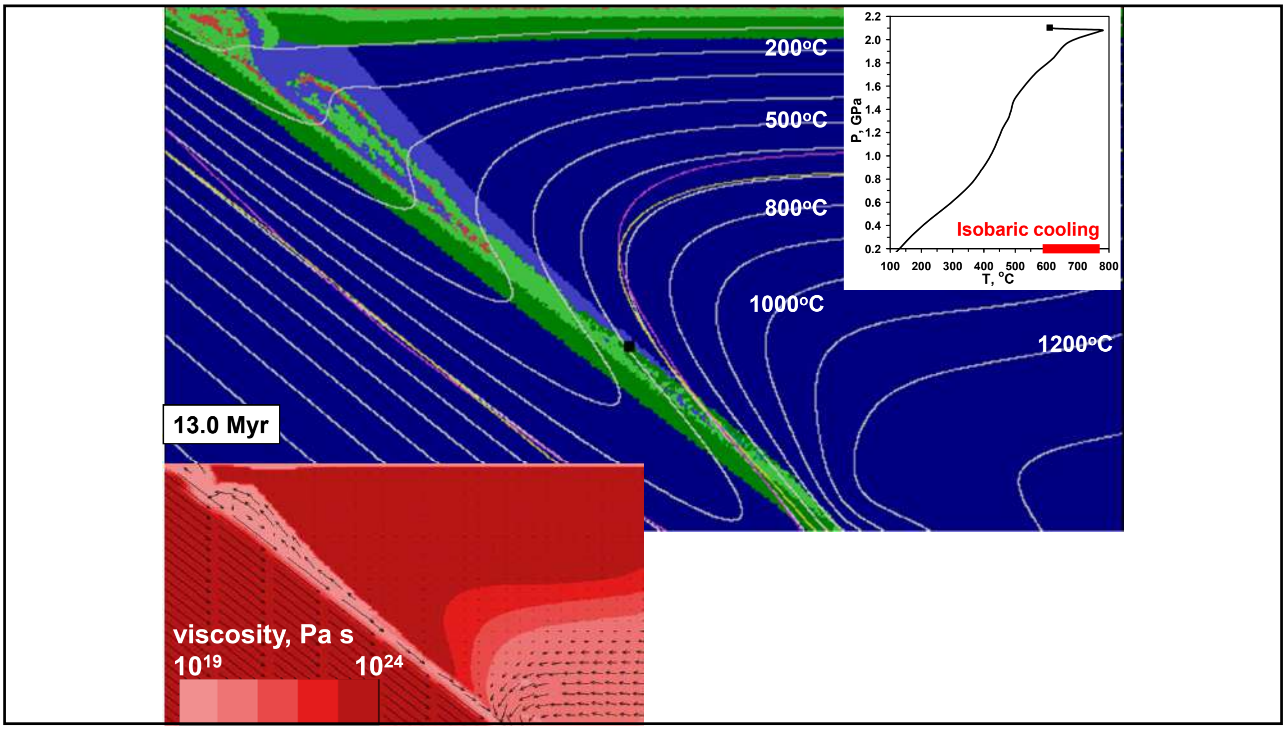

200°C
500°C
800°C
1000°C
1200°C
8.3 Myr
P, GPa
T, °C
Isobaric cooling
viscosity, Pa s
10^19
10^24

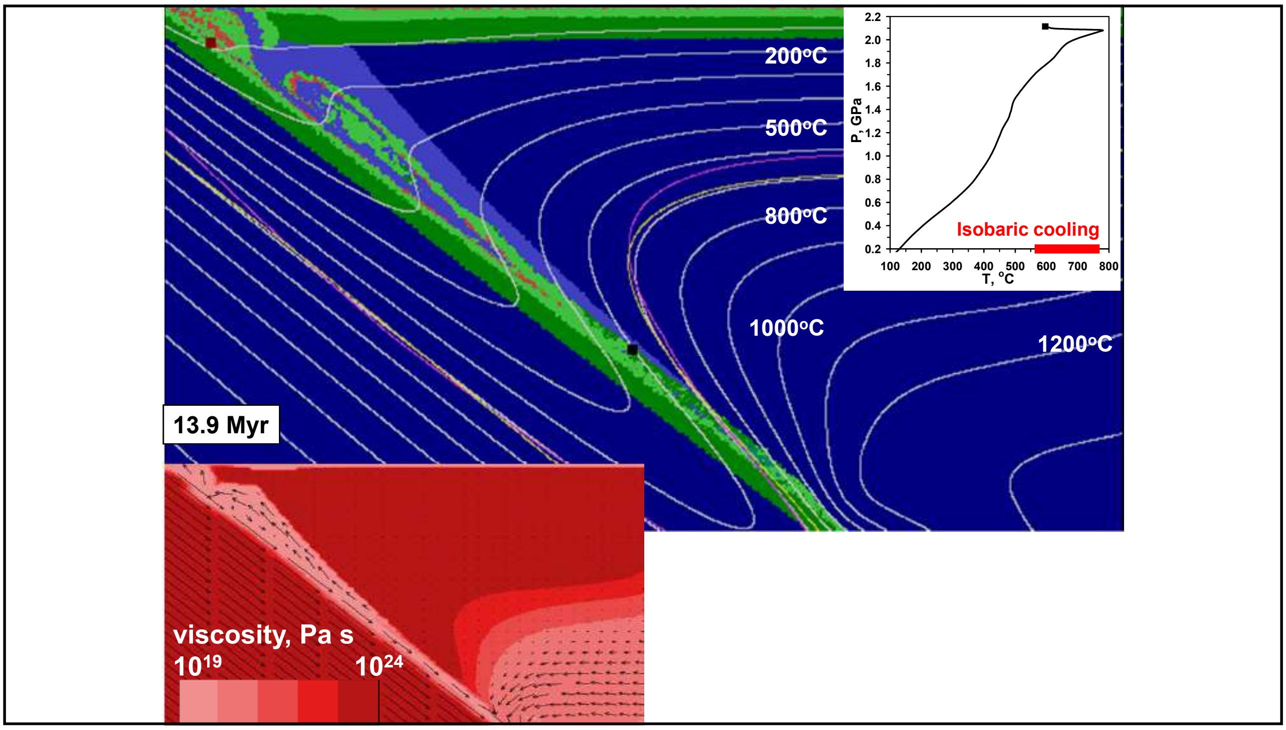

200°C
500°C
800°C
1000°C
1200°C
9.3 Myr
P, GPa
T, °C
Isobaric cooling
viscosity, Pa s
10^{19}
10^{24}

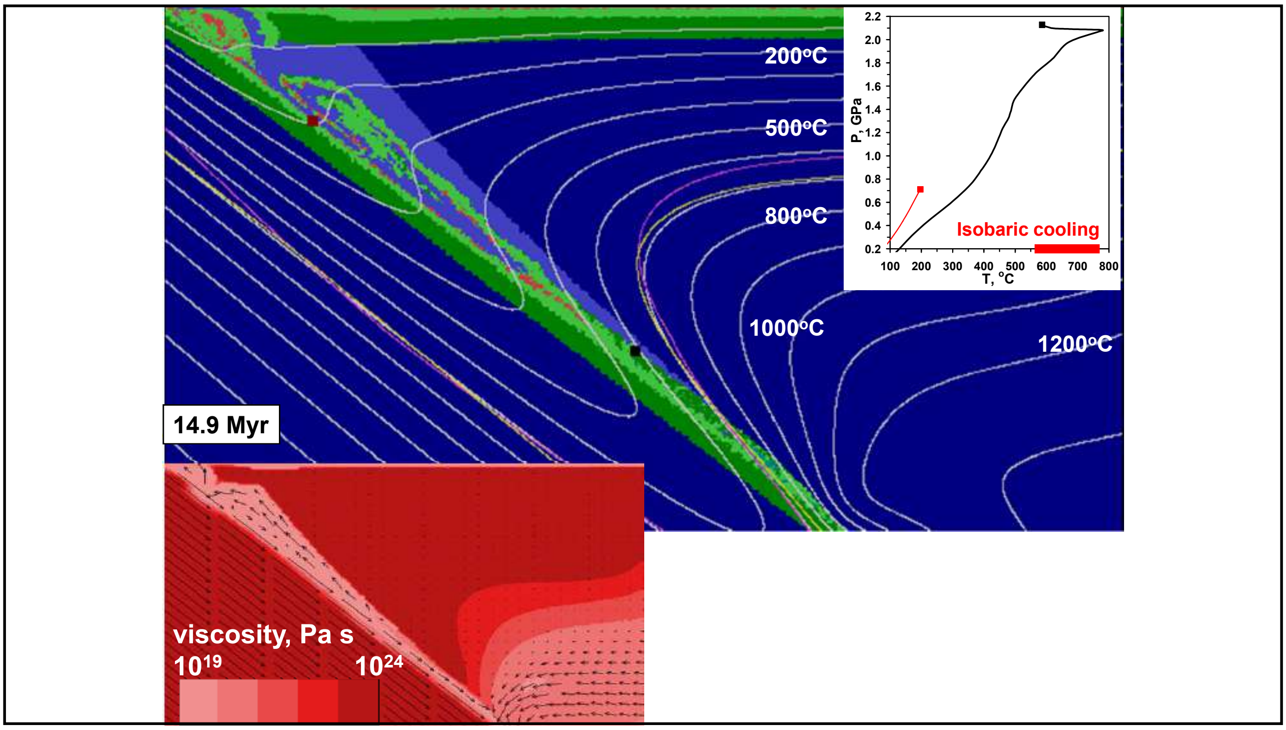

200°C
500°C
800°C
1000°C
1200°C
10.2 Myr
P, GPa
T, °C
Isobaric cooling
viscosity, Pa s
10^{19}
10^{24}

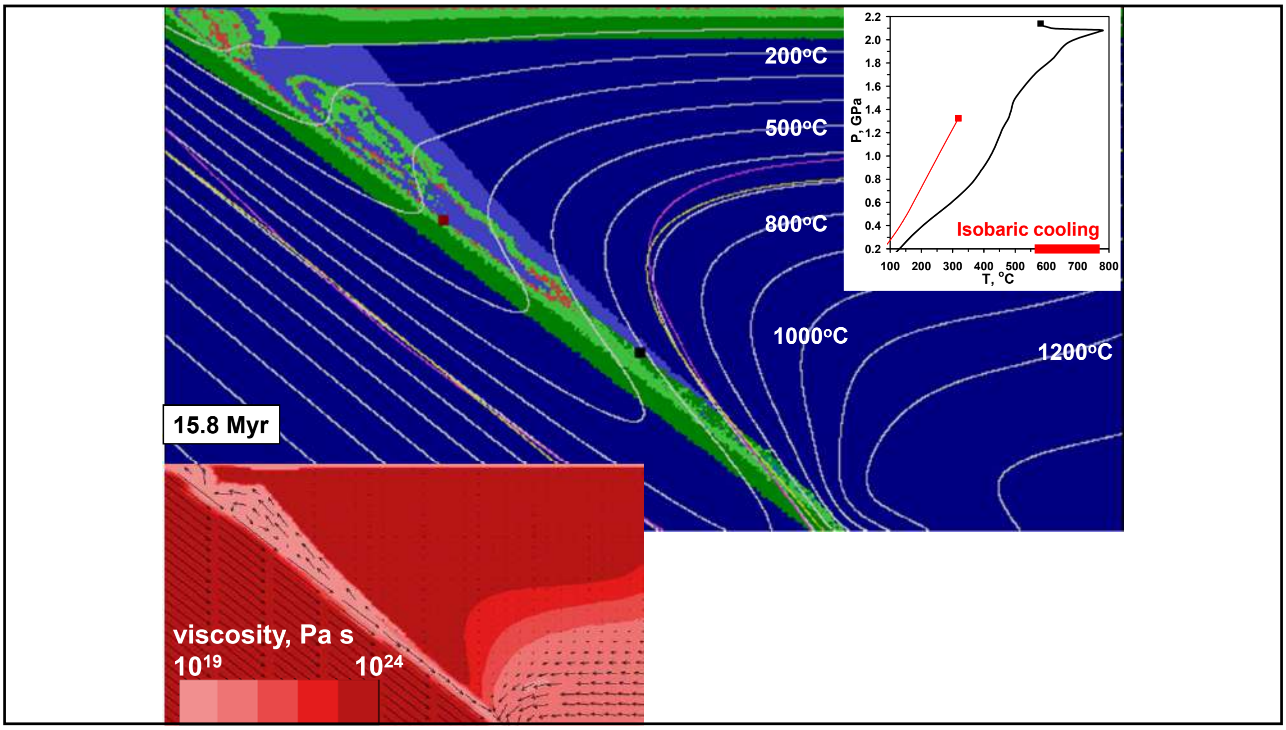

200°C
500°C
800°C
1000°C
1200°C
11.2 Myr
viscosity, Pa s
10^{19}
10^{24}
P, GPa
T, °C
Isobaric cooling

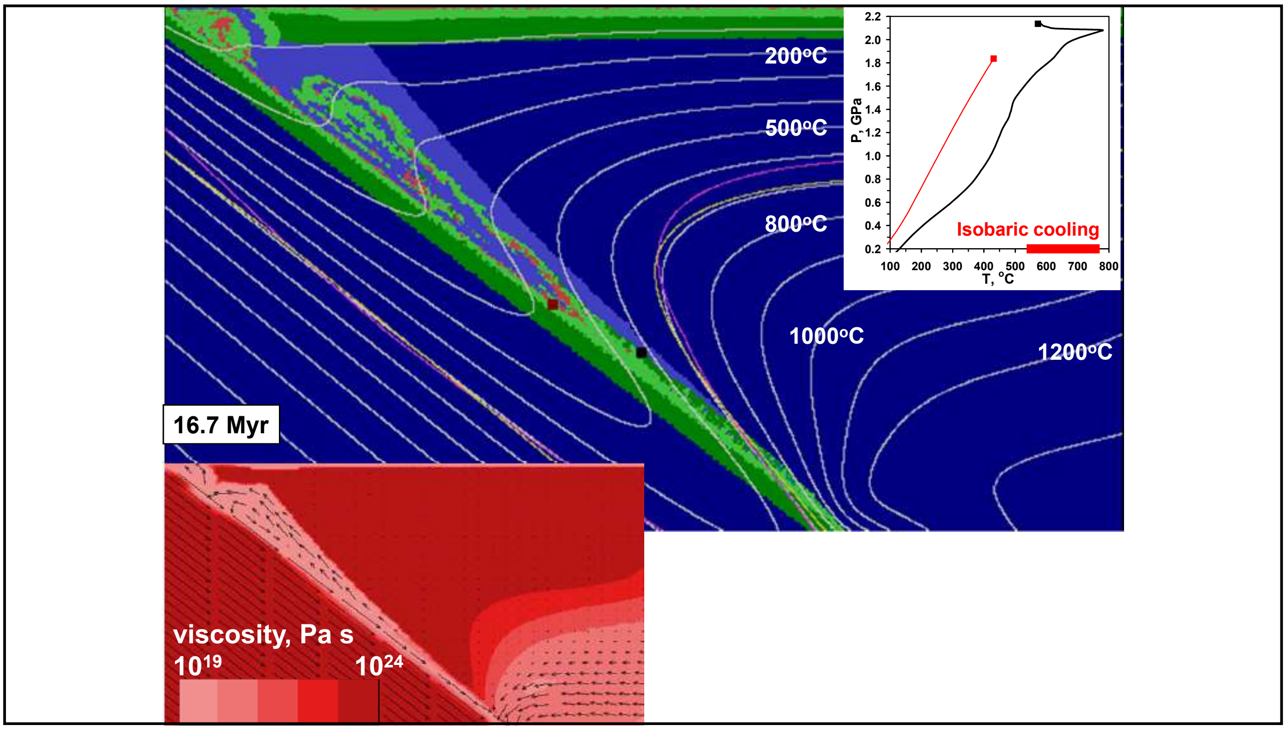

200°C
500°C
800°C
1000°C
1200°C
12.1 Myr
viscosity, Pa s
10^{19}
10^{24}
P, GPa
T, °C
Isobaric cooling

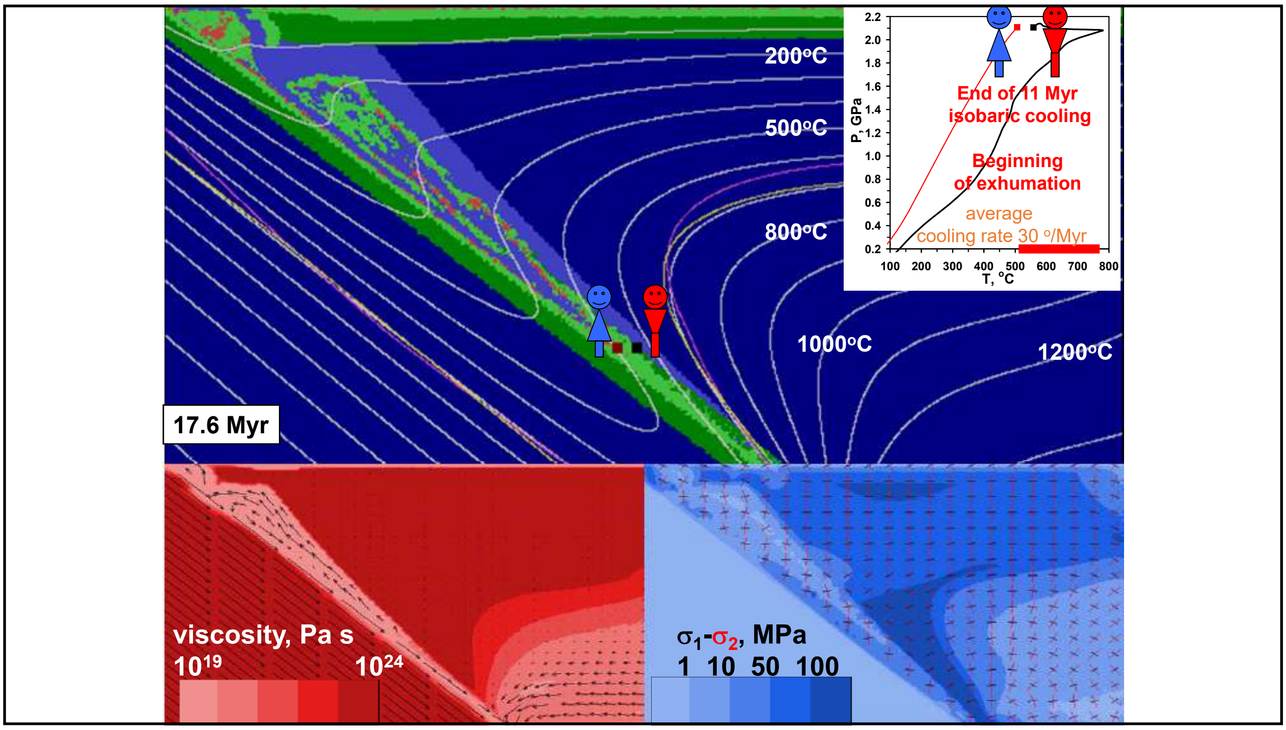

200°C
500°C
800°C
1000°C
1200°C
13.0 Myr
P, GPa
T, °C
Isobaric cooling
viscosity, Pa s
10^{19}
10^{24}

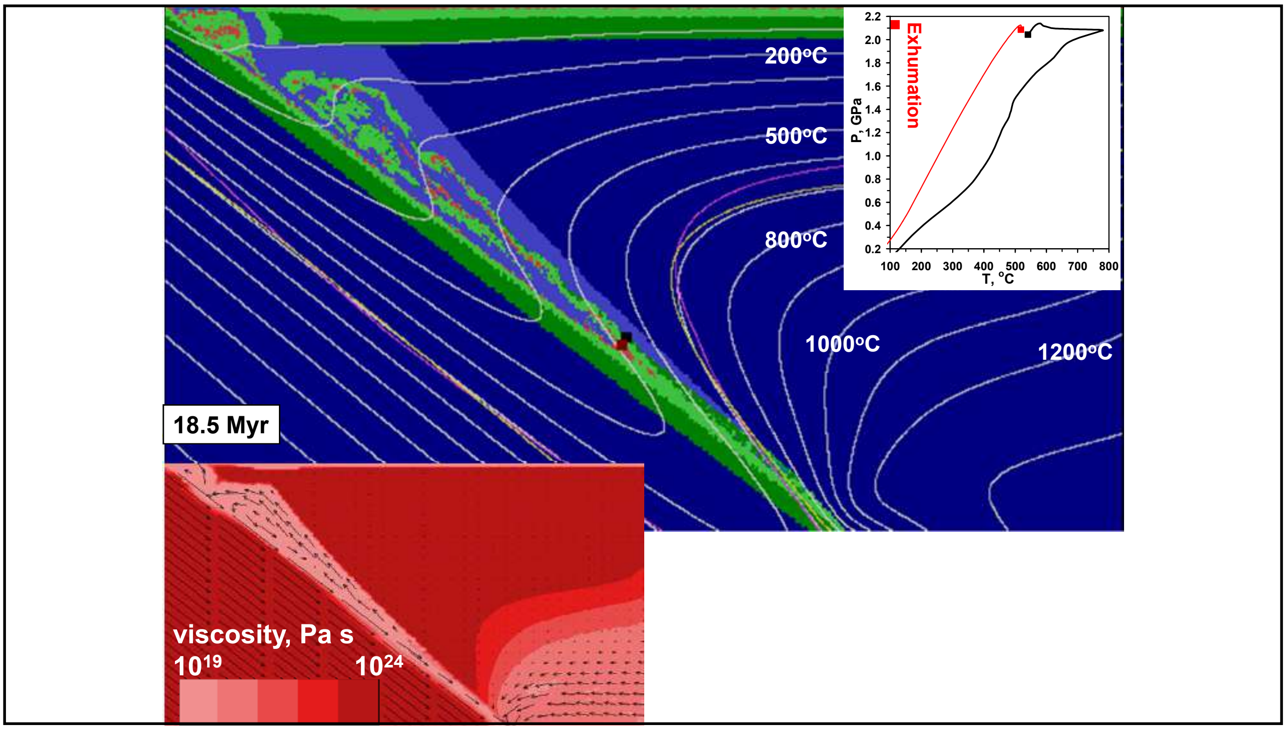

200°C
500°C
800°C
1000°C
1200°C
13.9 Myr
P, GPa
T, °C
Isobaric cooling
viscosity, Pa s
10^{19}
10^{24}


200°C
500°C
800°C
1000°C
1200°C
14.9 Myr
Isobaric cooling
P, GPa
T, °C
viscosity, Pa s
10^{19}
10^{24}

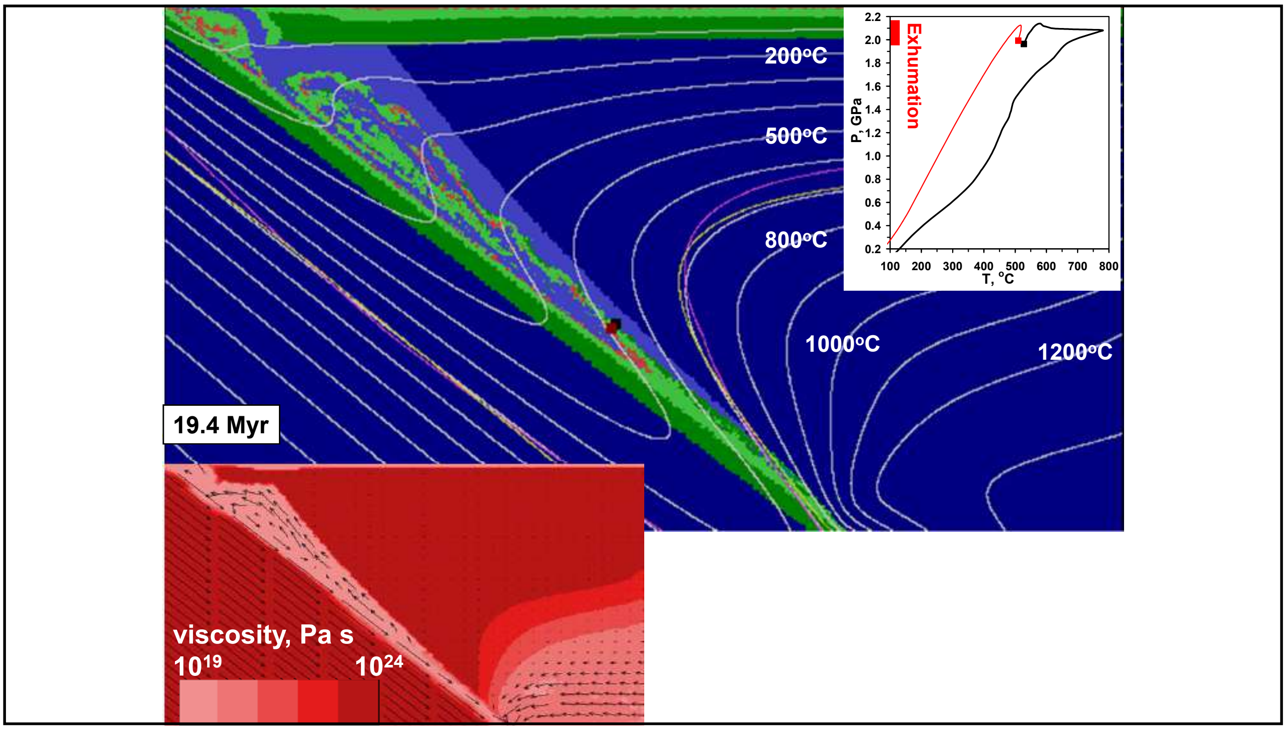

200°C
500°C
800°C
1000°C
1200°C
15.8 Myr
Isobaric cooling
P, GPa
T, °C
viscosity, Pa s
10^{19}
10^{24}


200°C
500°C
800°C
1000°C
1200°C
16.7 Myr
P, GPa
T, °C
Isobaric cooling
viscosity, Pa s
10^{19} 10^{24}

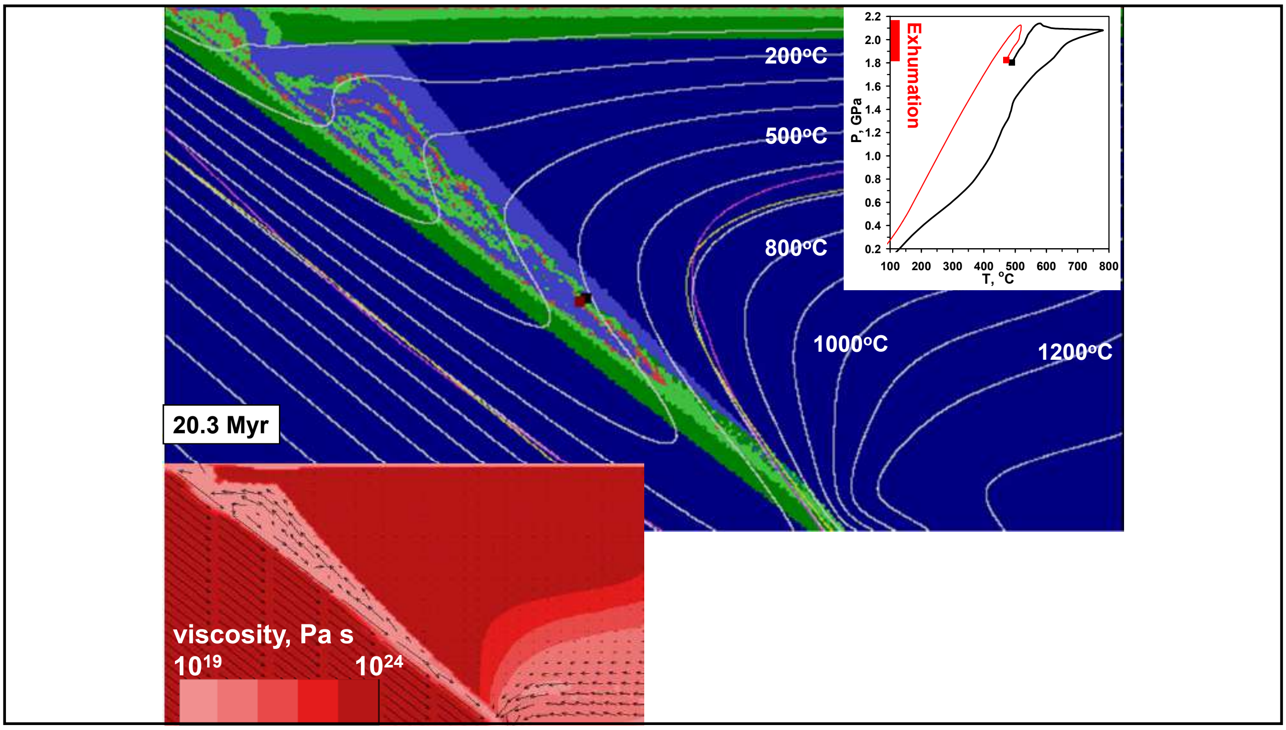

200°C
500°C
800°C
1000°C
1200°C
17.6 Myr
P, GPa
T, °C
End of 11 Myr
isobaric cooling
Beginning
of exhumation
average
cooling rate 30 °/Myr
viscosity, Pa s
10^{19} 10^{24}
σ_1-σ_2, MPa
1 10 50 100

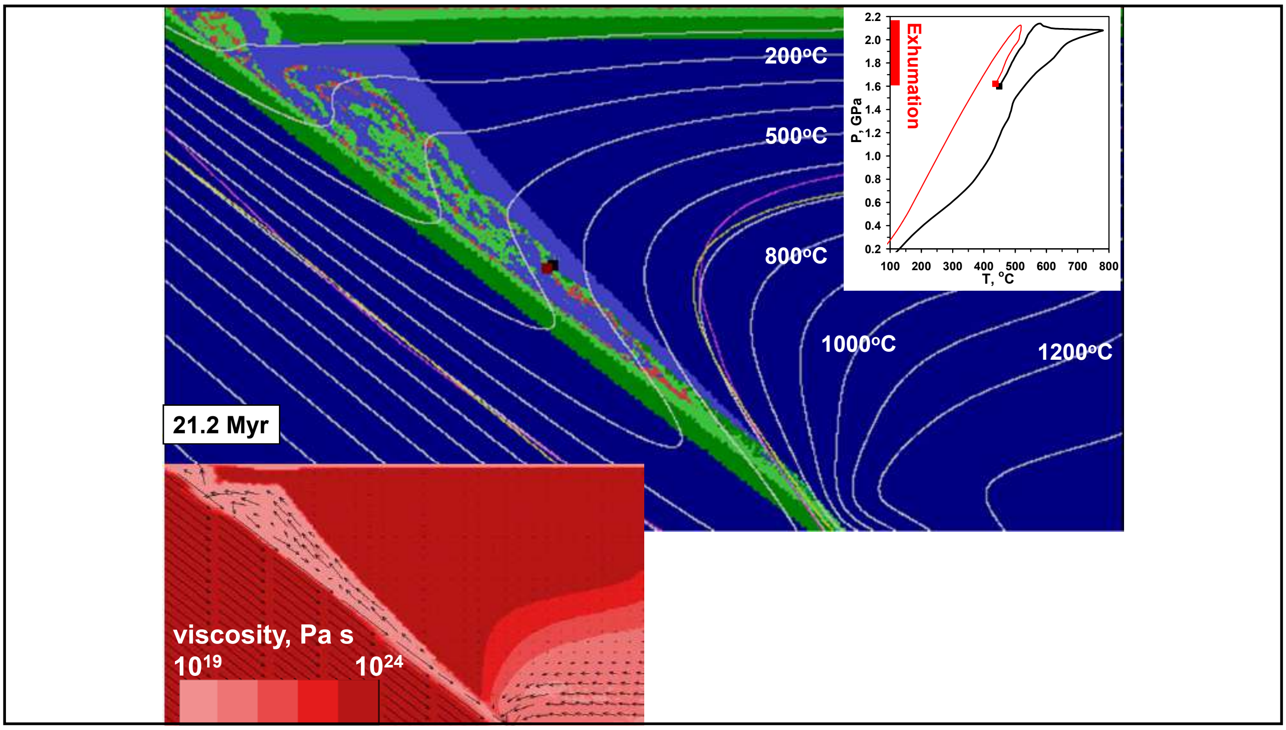


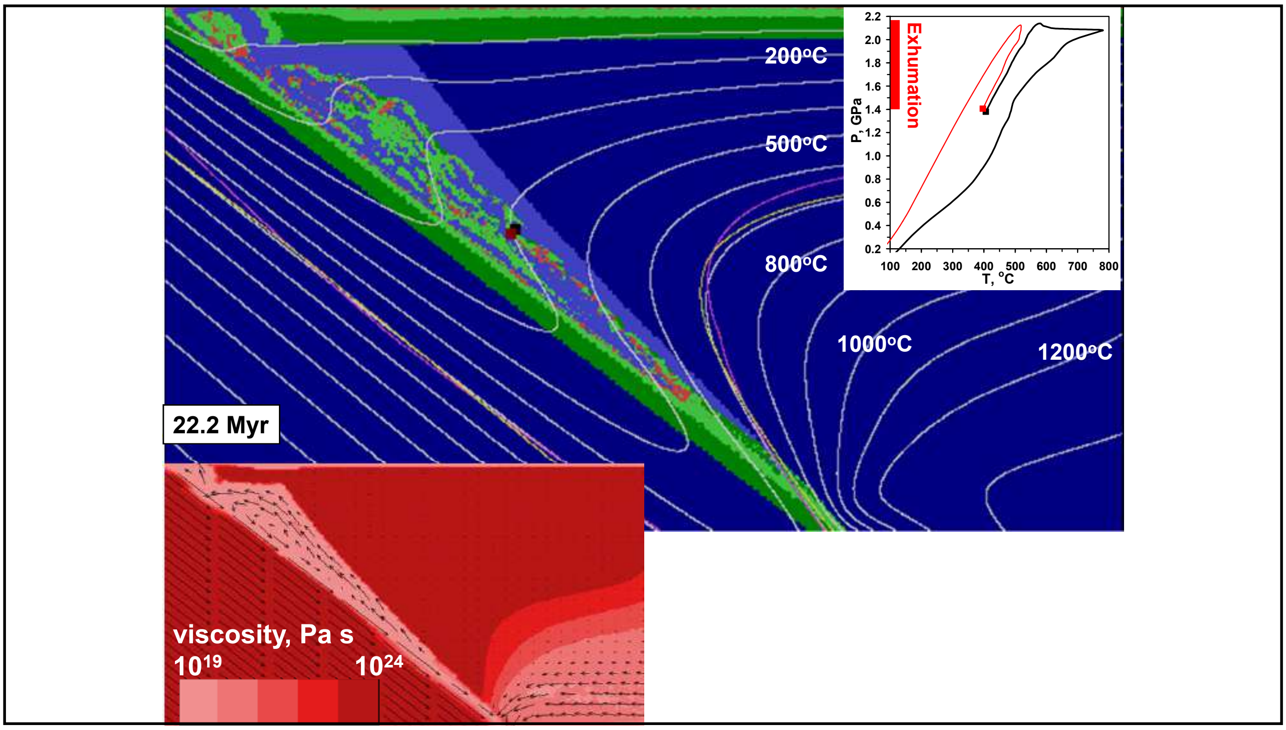
200°C
500°C
800°C
1000°C
1200°C
18.5 Myr
Exhumation
P, GPa
T, °C
viscosity, Pa s
10^19
10^24

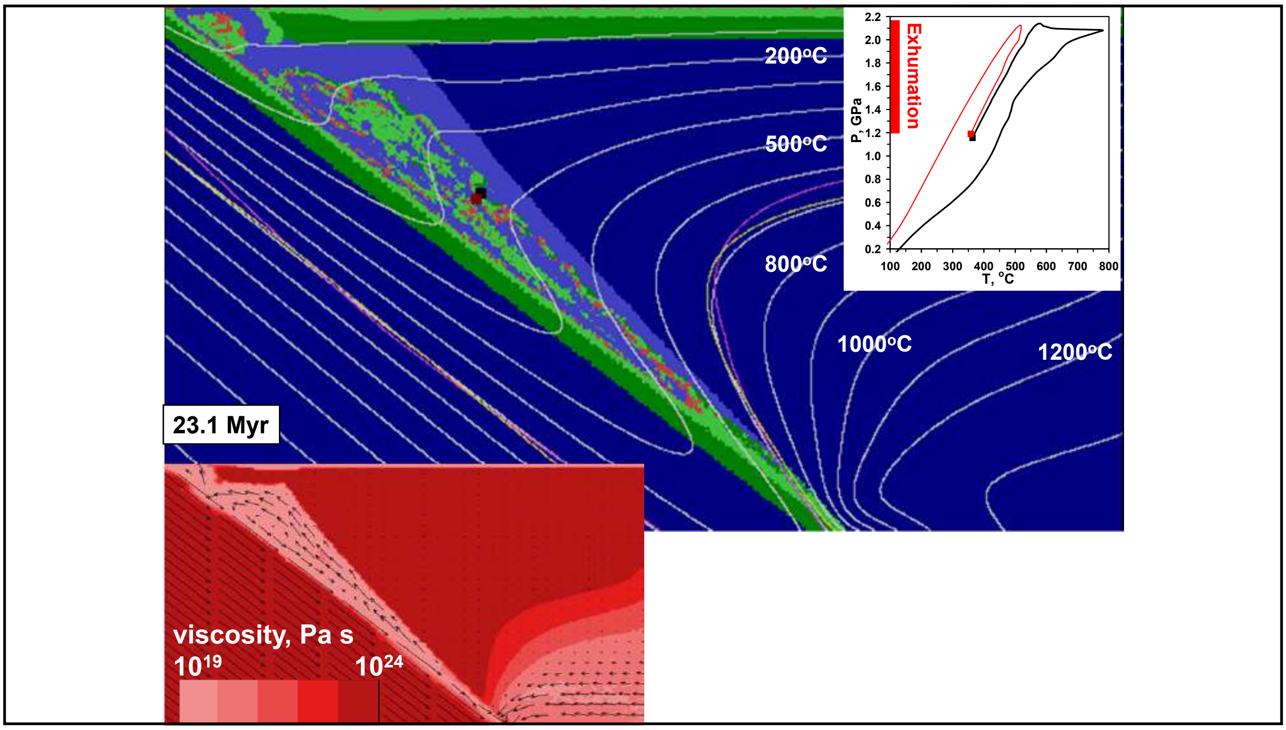


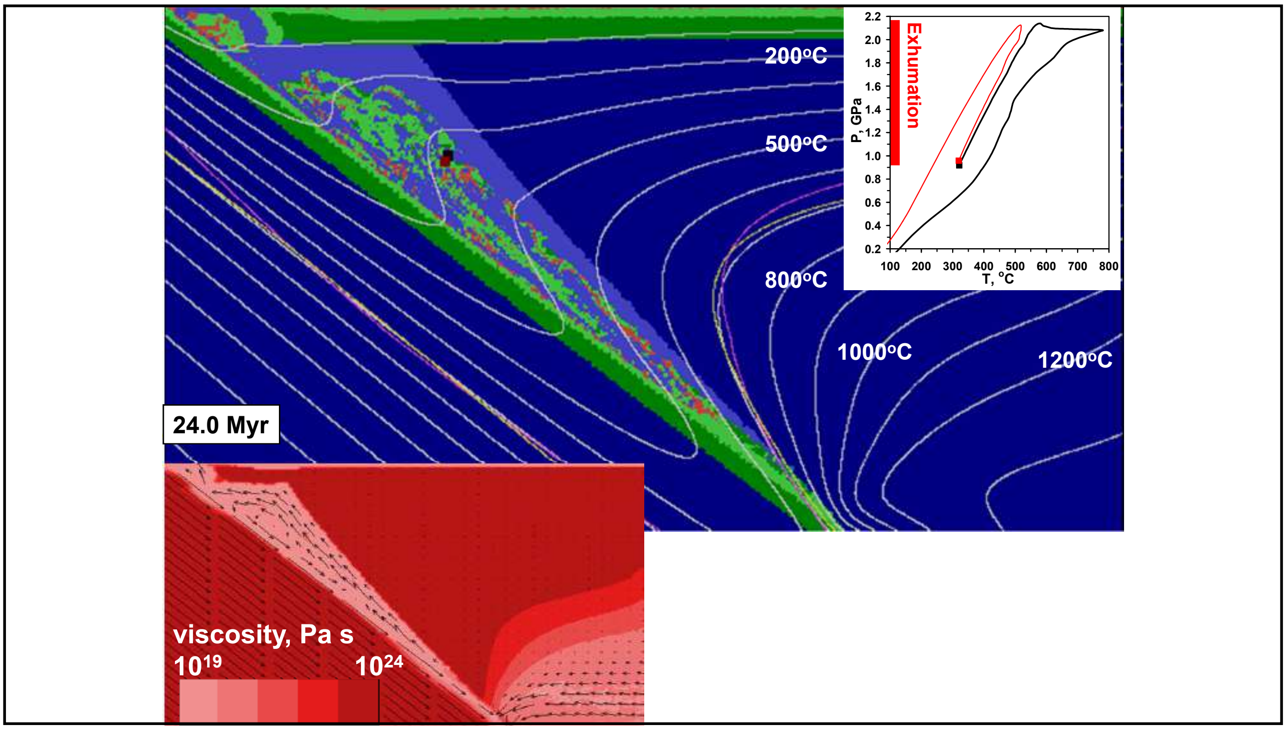
200°C
500°C
800°C
1000°C
1200°C
19.4 Myr
Exhumation
P, GPa
T, °C
viscosity, Pa s
10^19
10^24


200°C
500°C
800°C
1000°C
1200°C
20.3 Myr
viscosity, Pa s
10^{19}
10^{24}
Exhumation
P, GPa
T, °C

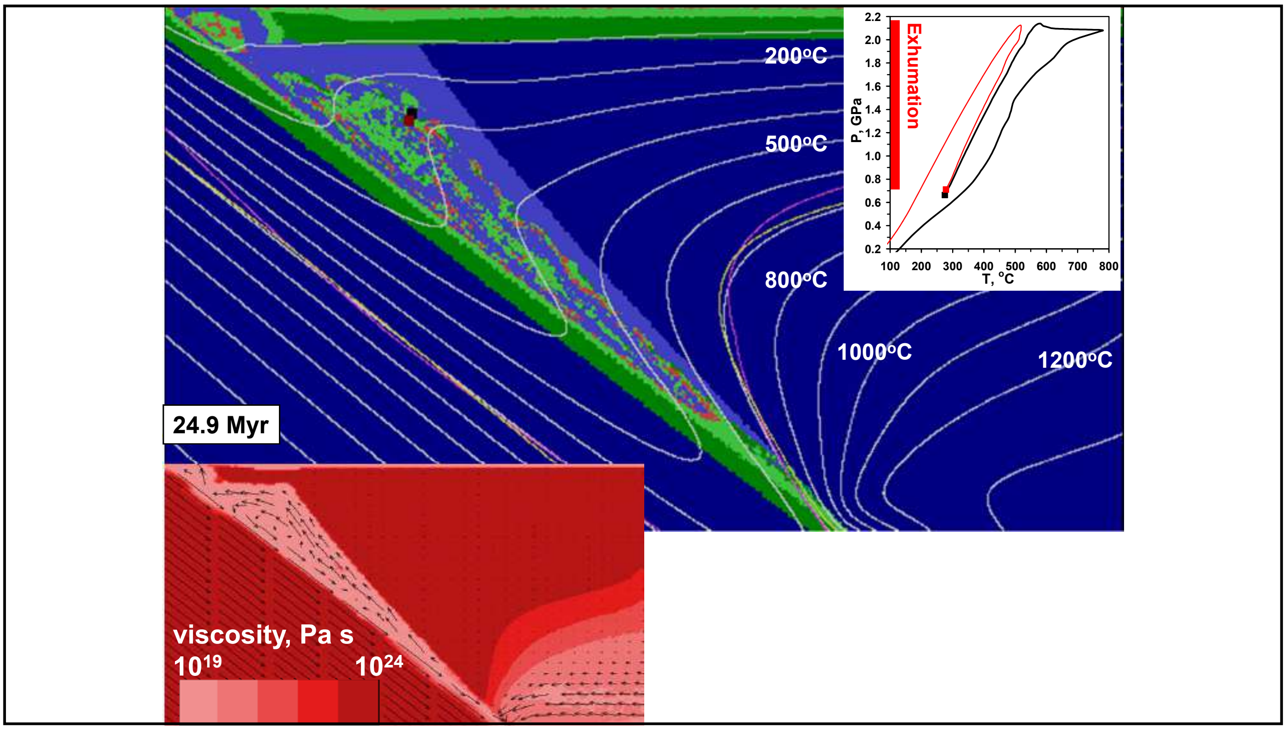

200°C
500°C
800°C
1000°C
1200°C
21.2 Myr
viscosity, Pa s
10^{19}
10^{24}
Exhumation
P, GPa
T, °C


200°C
500°C
800°C
1000°C
1200°C
22.2 Myr
viscosity, Pa s
10^{19}
10^{24}
Exhumation
P, GPa
T, °C

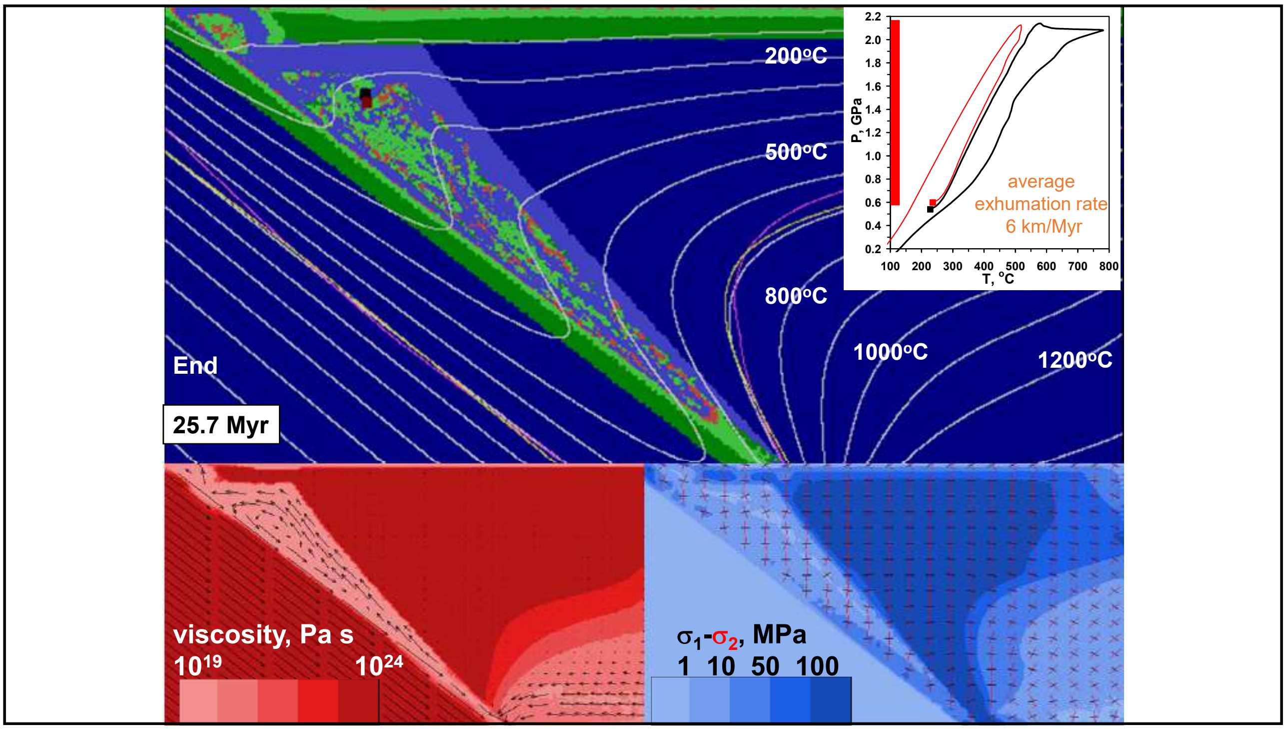

200°C
500°C
800°C
1000°C
1200°C
23.1 Myr
viscosity, Pa s
10^{19}
10^{24}
Exhumation
P, GPa
T, °C

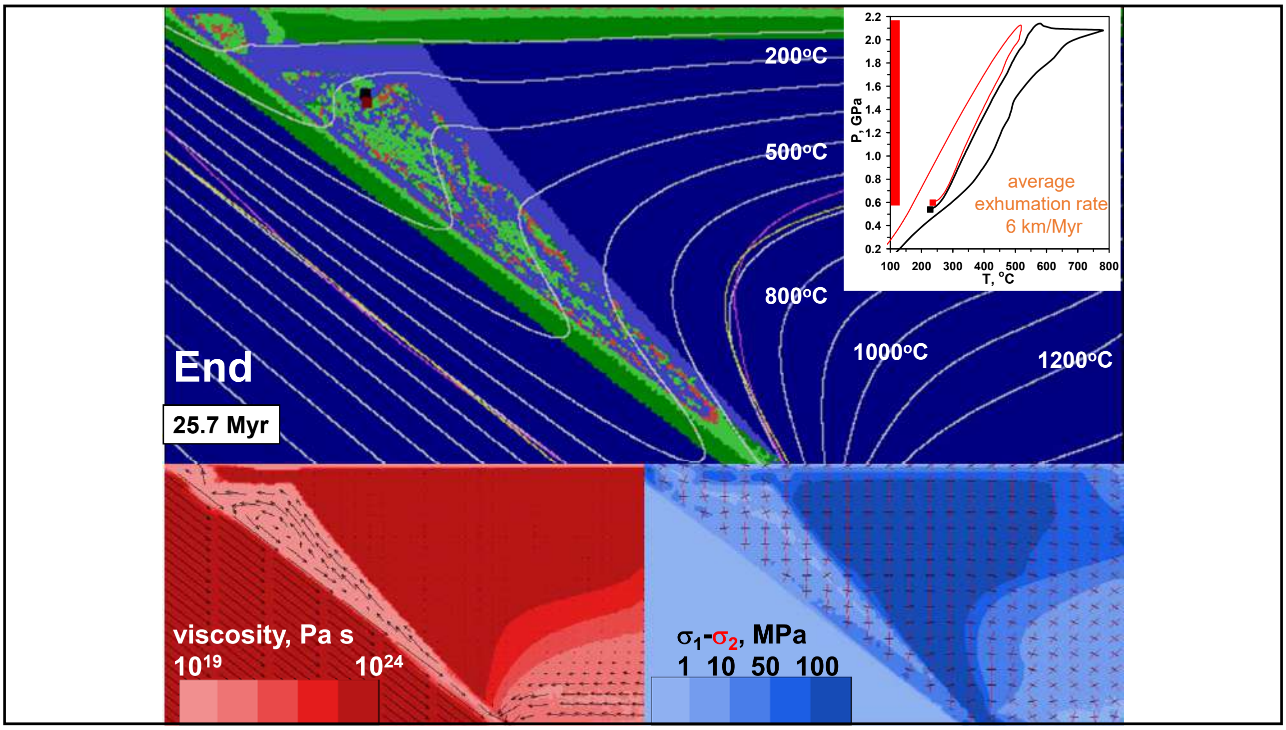


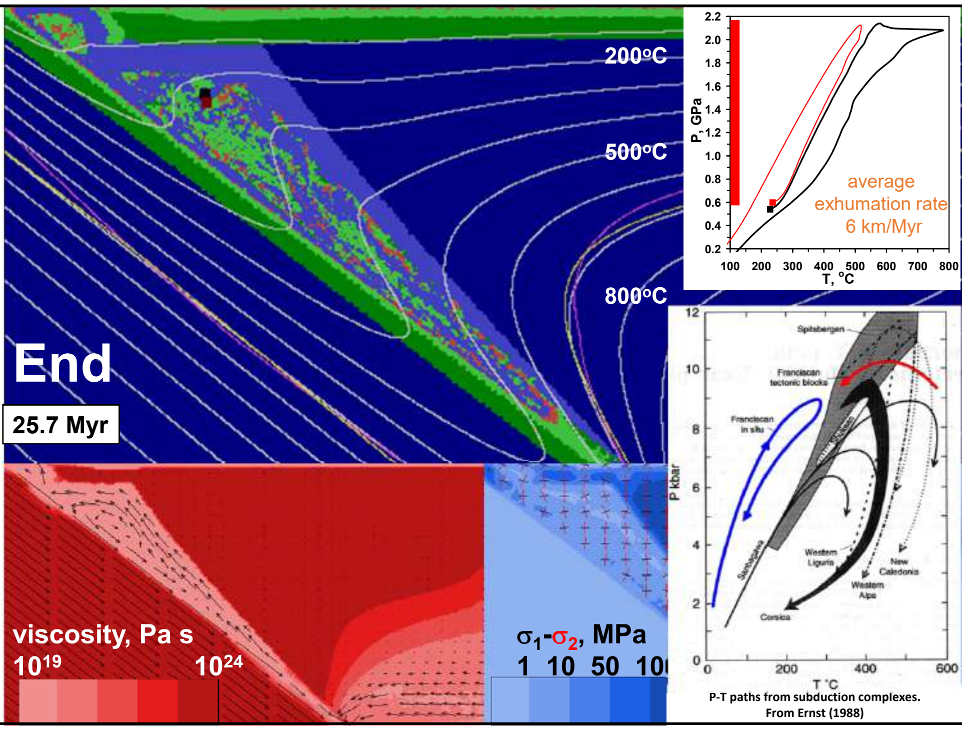
200°C
500°C
800°C
1000°C
1200°C
24.0 Myr
Exhumation
P, GPa
T, °C
viscosity, Pa s
10^{19}
10^{24}



200°C
500°C
800°C
1000°C
1200°C
24.9 Myr
Exhumation
P, GPa
T, °C
viscosity, Pa s
10^{19}
10^{24}


200°C
500°C
800°C
1000°C
1200°C
End
25.7 Myr
P, GPa
T, °C
average
exhumation rate
6 km/Myr
viscosity, Pa s
10^19 10^24
σ1-σ2, MPa
1 10 50 100


200°C
500°C
800°C
1000°C
1200°C
End
25.7 Myr
P, GPa
T, °C
average
exhumation rate
6 km/Myr
viscosity, Pa s
10^19 10^24
σ1-σ2, MPa
1 10 50 100



Next Lecture

Deformation of Rocks

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 15. Deformation of Rocks - I

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Do the rocks deform?
- The subjects “Structural Geology”; “Tectonics” and “Geodynamics”
- Concepts of Scale, Continuity and Homogeneity

Reference:
Chapter 7, Grotzinger_Jordan’s Book

Do the rocks deform?

We use the term "Rock Solid"… but rocks indeed deform mostly because of the tectonic forces acting on them in presence of various magnitude of pressure and temperature

Photograph: Santanu Misra

Photograph: Santanu Misra

Do the rocks deform?

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Photograph: GNS Science, NZ

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Photograph: Santanu Misra

Photograph: Santanu Misra

Do the rocks deform?

We use the term "Rock Solid"… but rocks indeed deform mostly because of the tectonic forces acting on them in presence of various magnitude of pressure and temperature

Do the rocks deform?

- YES, Rocks do fracture and flow under force and produce various structures which are very important to understand the mechanics of earth globally or locally.
- The sub-discipline under which Geologists study the deformation of rocks are

  Structural Geology

  Tectonics, and

  Geodymanics

What is Structural Geology?

Structural Geology is commonly used together with **Tectonics** and **Geodynamics**

struere *(latin)* : **build**

tektos *(greek)* : **builder**

dunamis *(greek)* : **power, force**

The subject concerns in general with the shape (geometry), displacements (kinematics) and forces (mechanics) in Earth and Planetary bodies

Structural Geology / Tectonics / Geodynamics

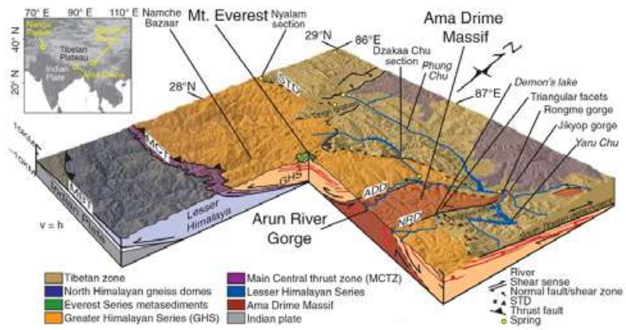
- **Structural Geology** characterizes the deformation structures, displacements (kinematics), and forces that produced the deformation (dynamics). A field-based discipline, structural geology operates at scales ranging from 100 microns to 100 meters (i.e. grain to outcrop).

  Tools: Field-study, Rock Deformation, Analogue experiments, Numerical models.

Structural Geology / Tectonics / Geodynamics

- **Tectonics** picturizes the geological scenario (maps, cross sections, 3D presentations etc.) of deformation together with information from petrology, stratigraphy and geophysics. Tectonics operates at scales ranging from 100 m to 1000 km, mostly confined on the movement of the plates and their mutual-interactions (continental rifting and basins formation, subduction, collisional processes and mountain building processes etc.).

  Tools: Field-study, Analogue experiments, Numerical models.

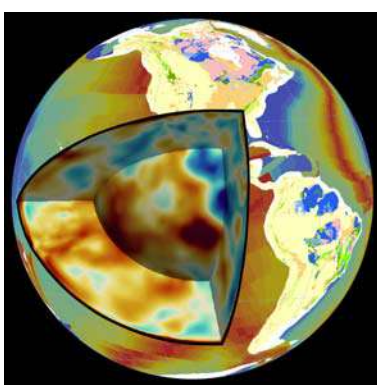


GSA Guest Blog, M. J. Jessup, 2013

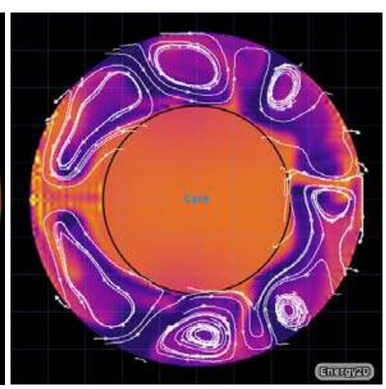
Structural Geology / Tectonics / Geodynamics

- **Geodynamics** discusses about the forces and processes drive the plate tectonics, and deformation of materials inside the earth (mantle convection, plumes etc.). The study of Geodynamics operates at scales > 100 km.

  Tools: Analogue experiments, Numerical Models



https://unixtitan.net



https://concord.org

A few things to remember

SCALE

CONTINUOUS
DISCONTINUOUS

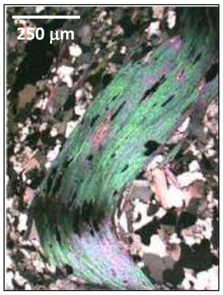
HOMOGENEOUS
HETEROGENEOUS

ISOTROPIC
ANISOTROPIC

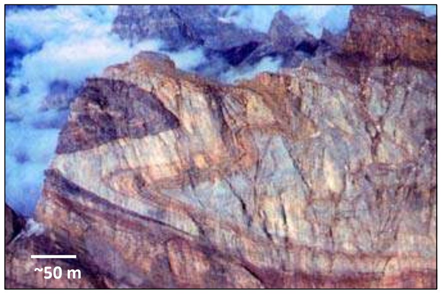
Scale

- There are classically three scales of investigation: ***microscopic***, ***mesoscopic***, and ***macroscopic***
  - **Microscopic** scale pertains to any structure so small ($<10^{-2}$ m) that it requires to be examined with an optical or electron microscope. [*microscopic scale*]
  - **Mesoscopic** scale pertains to any structure that can be observed without the aid of the microscope on a hand specimen or a single outcrop (10^{-2} to 10^{2} m). [*outcrop scale*]
  - **Macroscopic** scale pertains to structures that are too large ($>10^{2}$ m) to be completely exposed in one outcrop, which implies the interpretative step of reconstructing the structure from data collected at a number of outcrops. [*field/regional scale*]

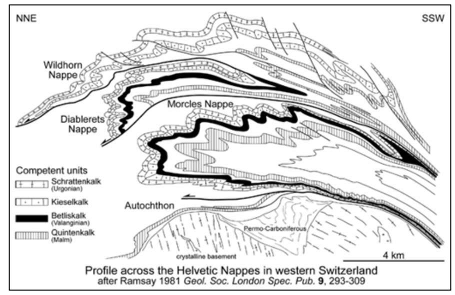
Scale



Folded biotite
microscope



Morcles Nappe (Dent de Morcles)
outcrop

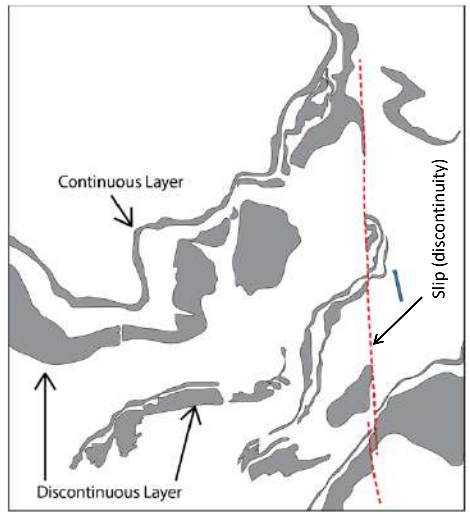


Morcles Nappe (Dent de Morcles)
field map

- The concept of scale is very important in structural geology. One must be constantly aware of the relationships between structures at all scales, and intellectually jump from one scale observation to another to solve the geometrical problems met in the field.

Continuous-Discontinuous

Continuous-Discontinuous



Basics of Ho-/He-/Iso-/Aniso-

- **Homogeneous Materials:**
  The term homogeneous is understood as "of uniform composition throughout" or "material composition and properties are independent of position."

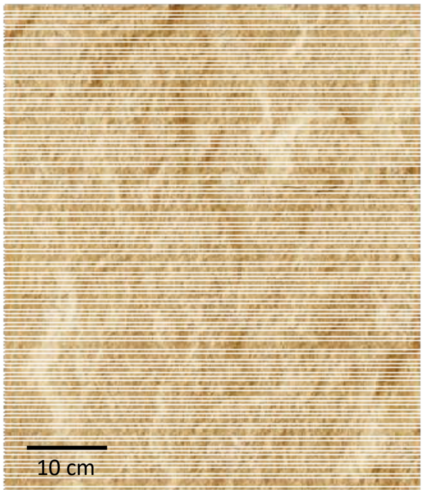
- **Heterogeneous Materials:**
  The term heterogeneous is understood as "of non-uniform composition throughout" or "material composition and properties varies with position. "

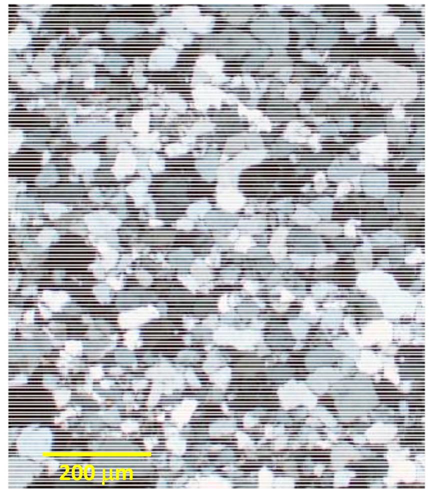
- **Isotropic Materials:**
  An isotropic material is one in which the physical properties are equal in all directions. In other words, material properties are independent of the direction in which they are measured.

- **Anisotropic Materials:**
  An anisotropic material is one in which the mechanical properties are not equal in all directions. In other words, material properties varies with the direction in which they are measured.

Note: The definitions above are absolutely **scale dependent**. For example, Layered and foliated rocks are statistically homogeneous, anisotropic materials if the scale of the layering or fabric is small relative to the scale of deformation.

Homogeneous-Heterogeneous





A sandstone in mesoscale is visually ***homogeneous***, but ***heterogeneous*** in microscale

Isotropic-Anisotropic

The granite in the left is ***isotropic*** in this scale, but the gneiss in the left is layered and ***anisotropic*** (across the layering).

Summary

Am I looking at a deformed rock?

What is the scale of the structure I am looking at….

Is the rock and deformation, homogeneous or heterogeneous?

Is the rock isotropic or anisotropic?

Next Lecture

In this lecture we learnt the basics of how to look and observe the deformed rocks.

In the next lecture we shall further investigate this topic and try to classify the different ways to interpret the deformation features.

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 16. Deformation of Rocks - II

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Experimental Rock Deformation Laboratory

Different ways of studying Deformed Rocks

DIRECT METHODS

Geometric Models (Structural Analysis): *Qualitative or Quantitative*
a. 2D or 3D interpretation of form and orientation of structures
b. based on data obtained from field studies (mapping, geophysical data)
c. represented by cross sections and maps.

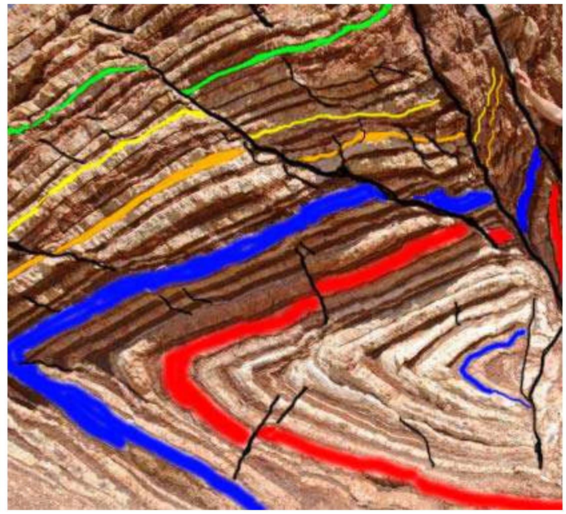
Kinematic Model (Strain Analysis): *mostly Quantitative*
a. reconstructing specific history of motion, displacement
(Plate tectonics is a kinematic model)

Mechanical Model (Dynamic Analysis): *Quantitative*
a. reconstructing the mechanical processes that resulted in rock deformation
b. deals with forces, rheology, deformation mechanism etc.

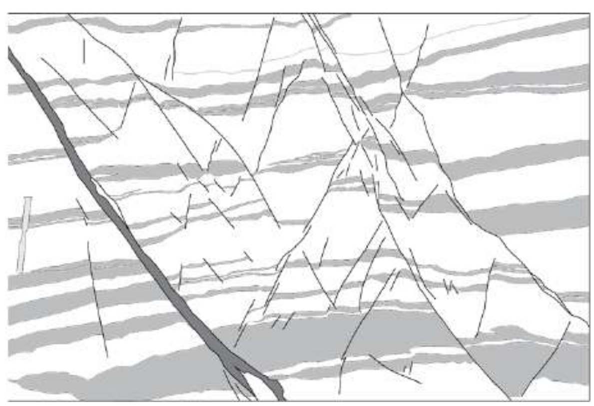
INDIRECT METHODS

Analytical Model
a. hypothesis
b. model derivation
c. additional data collection
d. compare with natural observations

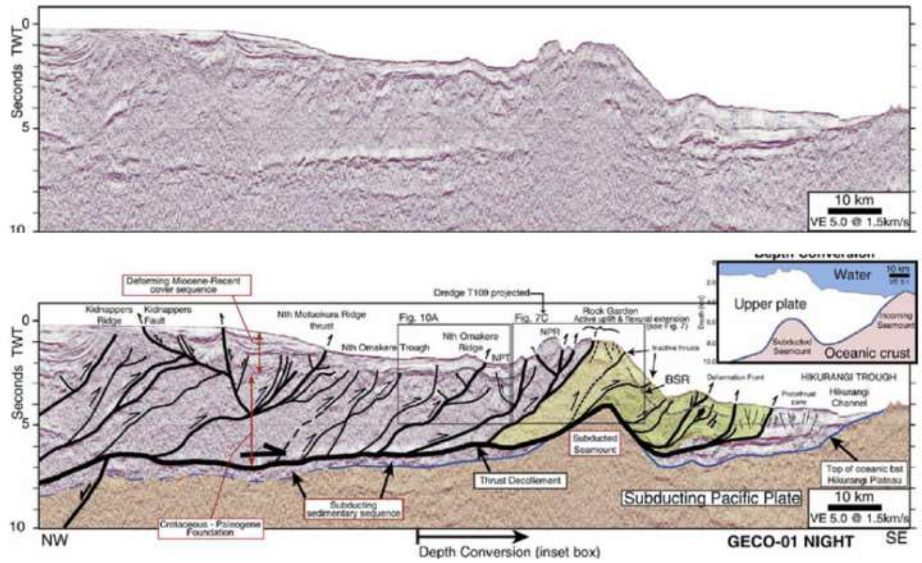
Geometric Model - Example



Geometric Model - Example

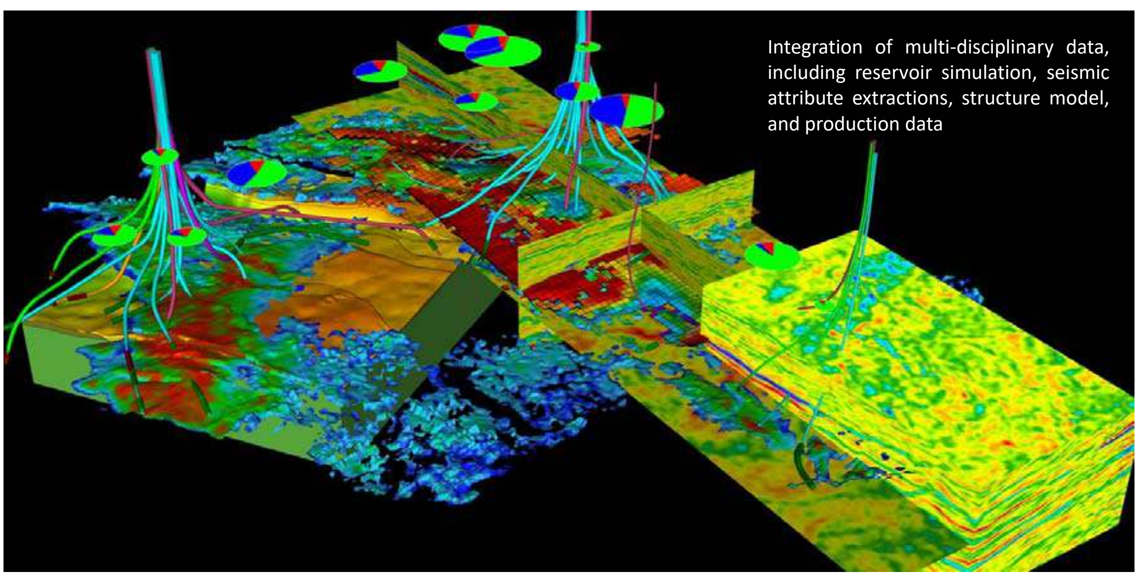


Geometric Model - Example



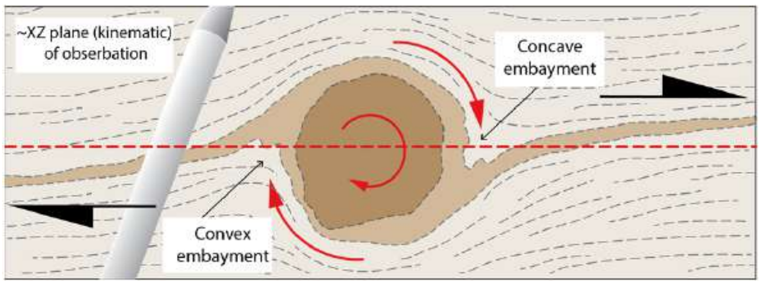
Lamarche et al., 2008

Geometric Model - Example

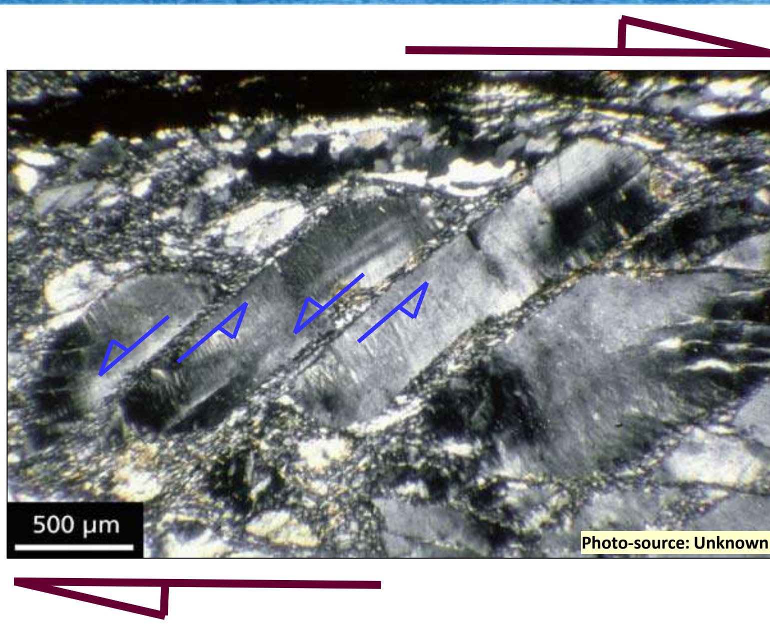


Dynamic Graphics (www.dgi.com)

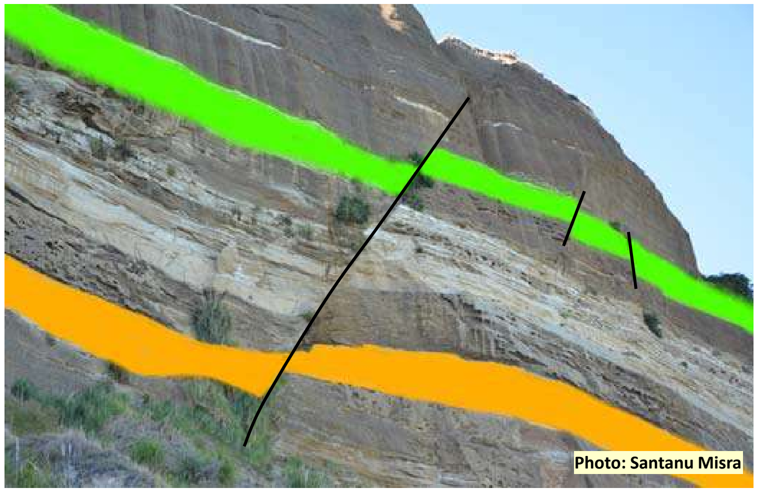
Kinematic Model - Example



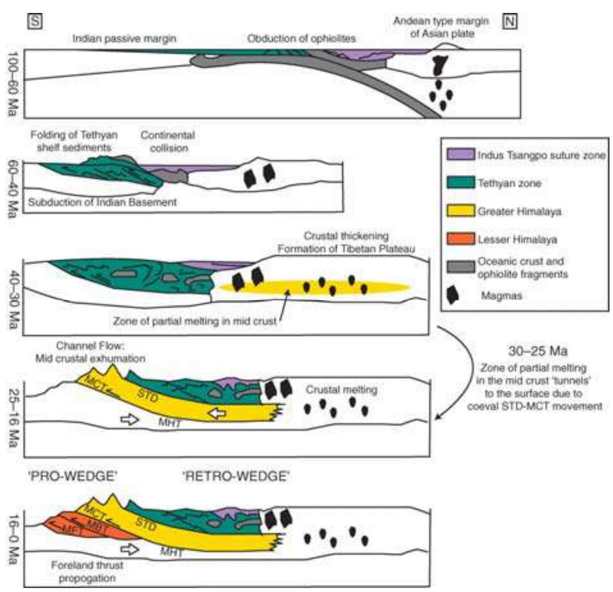
Kinematic Model - Example



Kinematic Model - Example

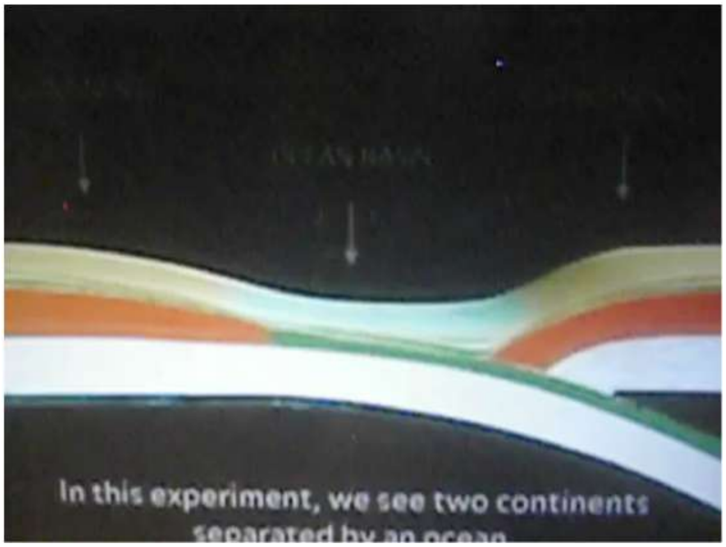


Kinematic Model - Example



Streule et al., 2010

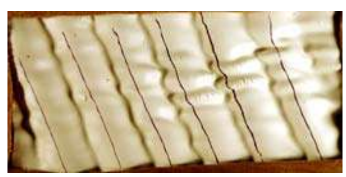
Dynamic Model - Example



Dynamic Models - Example

Superposition of folding

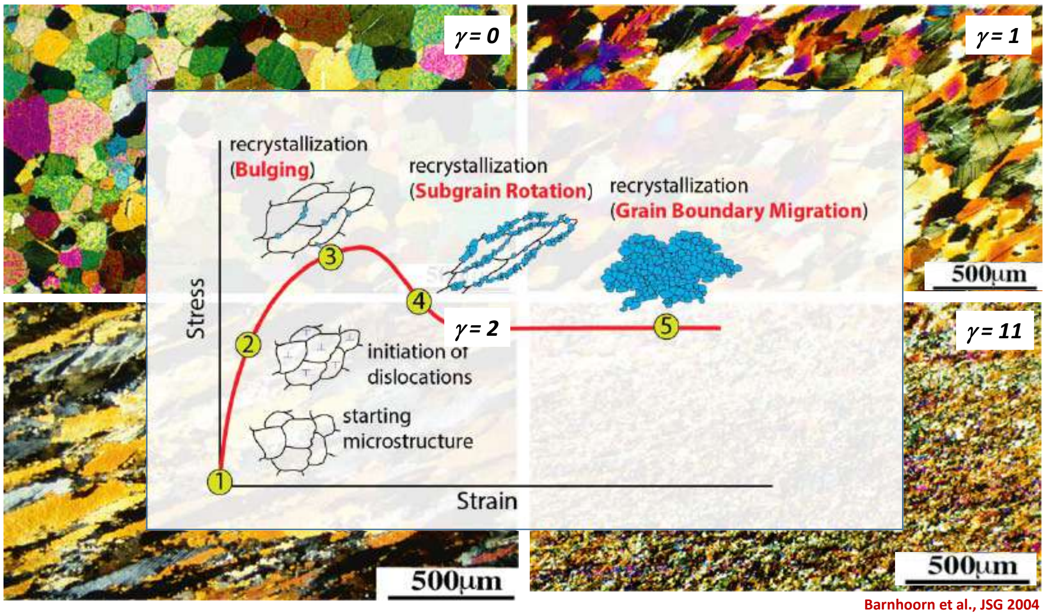

Stage 1


Stage 2


Stage 3


Stage 4

Dynamic Models - Example



Barnhoorn et al., JSG 2004

Dynamic Models - Example

Next Lecture

To understand the structures, it is important to identify and measure different ***structural elements*** (lines, planes and their mutual relationships). In the next lecture, we shall cover this topic.

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 17. Structural Elements

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Basic concepts of geological contacts and there applications in Structural Geology
- Attitudes of Planar, linear and angular features – what to measure and why?
- Concept of structural measurements
- Planar and linear features and their measurements

Structural Measurements – what and why?

- Understanding the structures in field is puzzling. This is mostly because, the exposures are not always continuous, difficult to access and all features are not present everywhere. These unavoidable characteristics of field geology, particularly for the interpretation of large structures, make the subject extremely challenging.

- Most of the geological observations, particularly in large scale (a few 100 meters or more), are generally two dimensional. The observations are usually presented in a map and the third dimension (relief or depression) is considerably negligible. However, geological structures are essentially three dimensional and one has to interpret the 3D geometry of the structures, unless considered otherwise.

- Rocks display various types of geometric elements are different scales. The elements can be broadly classified as planer- and linear-elements. Bedding, foliations, schistosity, cleavage etc. can be considered as ***planes*** whereas geological features like fold axes, mineral lineation, and paleocurrent directions are ***lines***.

Stratigraphic Sequence (geological contacts)

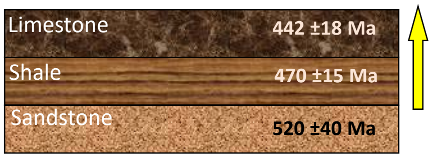
- The establishment of the lithological and/or stratigraphic sequence is a prerequisite in interpreting the large-scale structures and the history of an area.

- Any structural information has little meaning without its lithological (sedimentological or petrological) and age (paleontological or radiometric) context.

ERA	PERIOD	EPOCH	AGE*	MAJOR EVENTS
CENOZOIC	Quaternary	Holocene		
		Pleistocene	0.01	Earliest *Homo sapiens*
	Tertiary	Pliocene	1.8	Earliest hominids
		Miocene	5.3	
		Oligocene	23.8	
		Eocene	33.7	Dominance of mammals
		Paleocene	55	
MESOZOIC	Cretaceous		65	*Widespread extinctions*
	Jurassic		145	First flowering plants
	Triassic		200	Dinosaurs dominant
PALEOZOIC	Permian		251	*Widespread extinctions*
	Carboniferous		299	
	Devonian		359	First reptiles
	Silurian		417	
	Ordovician		443	Fishes dominant
	Cambrian		490	First fishes
PRECAMBRIAN			542	*Appearance of fossils*
				Soft-bodied animals
			3000	First one-celled organisms
			4600	Origin of the earth

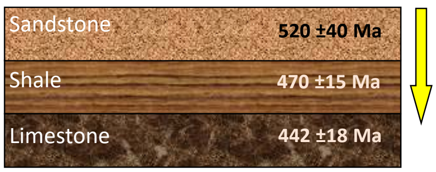
*Age in millions of years (Ma)

Stratigraphic Sequence (geological contacts)



Normal Sequence/Stratigraphy

Unconformity



Inverted Sequence/Stratigraphy

Repetition of Stratigraphic sequence

Stratigraphic Sequence – THINGS TO REMEMBER

- Layering in deformed metamorphic rocks (secondary layering) does not necessarily represent bedding. Thus it is important, wherever possible, to demonstrate the existence of bedding and stratigraphy, which can be obtained by identification of sedimentary structures that define the “way up” of the beds. Selecting a distinctive marker horizon is useful to picture regional structures.
- A deformation structure is necessarily younger than the age of the host rocks.
- An unconformity in stratigraphy marks the time of a major tectonic event.
- Inverted stratigraphy and/or repetition of stratigraphic sequence also suggest a single or multiple deformation events in the host rock.

What to measure?

The sediments are deposited (and/or precipitated) along horizontal planes and subsequently lithified to form rock-strata. After deformation, the horizontal strata do not necessarily remain horizontal.

southampton.ac.uk

What to measure?

The sediments are deposited (and/or precipitated) along horizontal planes and subsequently lithified to form rock-strata. After deformation, the horizontal strata do not necessarily remain horizontal.

www.sciencesource.com

https://creationontrial.com

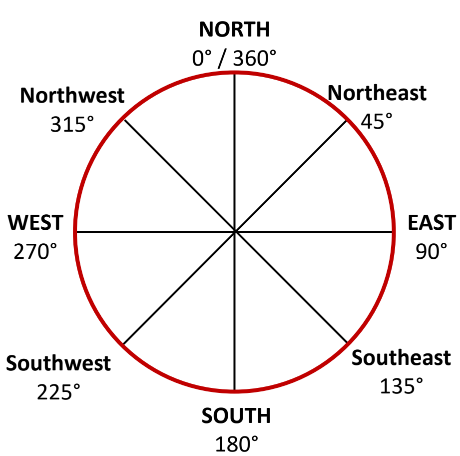
Structural Measurements – Basics

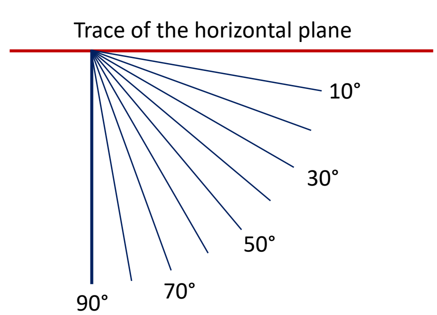
- **POINTS**
  - One set of coordinates
  - Distance and direction from a reference point
  - Intersection of two lines
  - Intersection of three planes
- **LINES**
  - Defined by two sets of coordinates
  - Defined by two points
  - Distance from a reference point & the direction of the line
  - Intersection of two planes
- **PLANES**
  - Defined by three sets of coordinates
  - Defined by three points
  - Defined by distance and direction from reference points/line
  - Defined by two intersecting or two parallel lines

Azimuth (Direction) and Inclination

Azimuth: measured along horizontal plane in degrees (°)

Inclination: measures the angle of tilt/slope at which the plane/line is oriented from the horizontal plane





A few common words of Structural Geologists

TREND DIP FRONT-BEARING

PLUNGE

STRIKE Attitude APPARENT-DIP

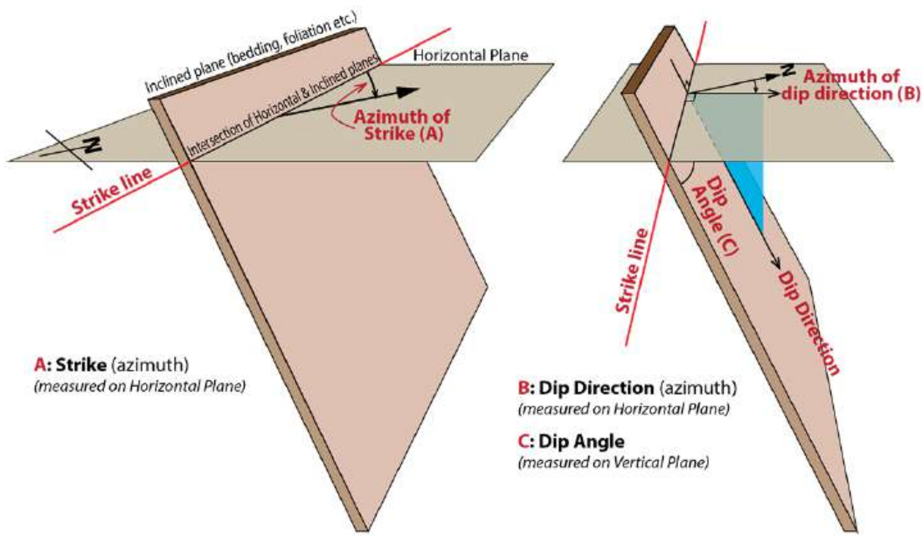
BACK-BEARING PITCH

RAKE Azimuth

DIP-ANGLE DIP-DIRECTION

All there are related to measurements of lines and planes

Orientations of Planes



RIGHT HAND RULE FOR MEASURING STRIKE. MAKES LIFE EASY.

Orientations of Planes

STRIKE:
Direction of the line of intersection between an inclined plane and a horizontal plane **OR** the strike is the compass direction of the horizontal line lying in an inclined plane

DIP ANGLE:

Inclination of a plane below the horizontal; 0°≤ dip ≤90° **OR** the dip is the large angle made by the plane with the horizontal

- *The azimuth directions of strike and dip are perpendicular.*

DIP DIRECTION:

The compass direction towards which the plane slopes

APPARENT DIP ANGLE/ DIRECTION:

Any dip angle/direction measured in a vertical plane that is not perpendicular to the strike line

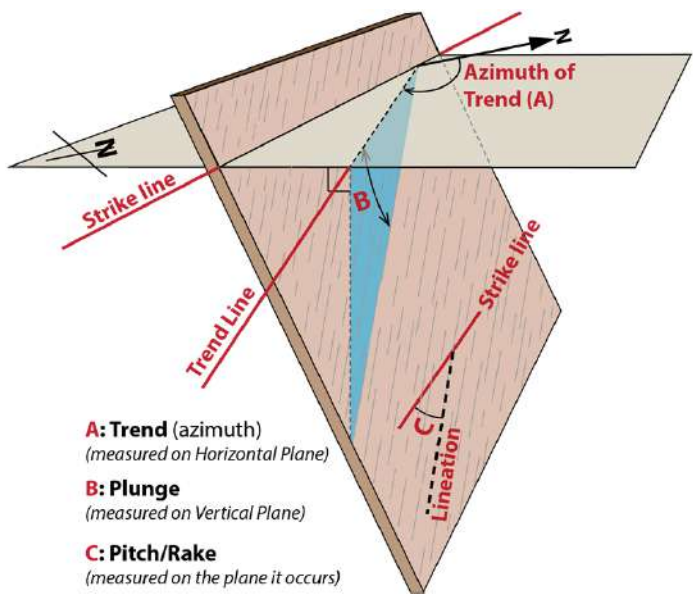
Structural Measurements – what and why?

TREND:
Direction (azimuth) of a vertical plane containing the line of interest.

The trend "points" in the direction a line plunges

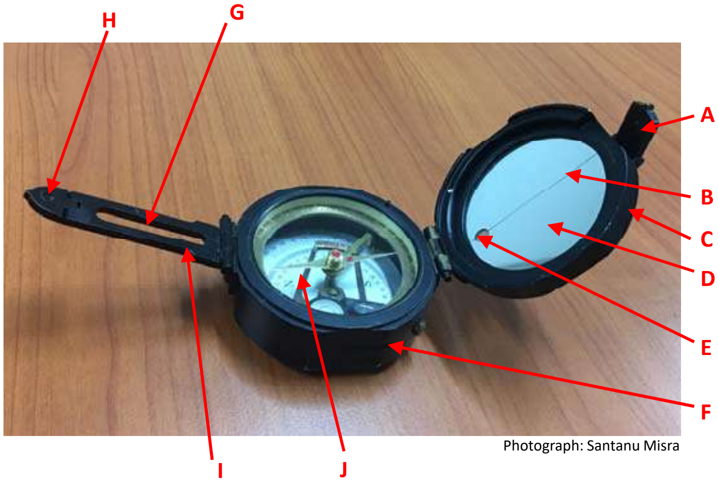
PLUNGE:
The inclination of a line below the horizontal

PITCH:
The angle, measured on a plane of specified orientation, between one line & a horizontal line (strike)



The tool to measure the orientation data

BRUNTON COMPASS *(there are many other compasses, you will be using Brunton)*



Photograph: Santanu Misra

A: Folding Sight

B: Axis Line

C: Lid

D: Mirror

E: Sighting Window

F: Base

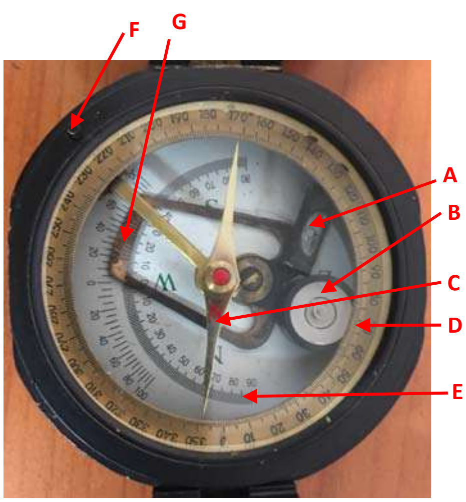
G: Open Slot

H: Peep Sight

I: Sighting Arm

J: Dial *(next slide)*

Parts of Brunton Compass



Photograph: Santanu Misra

A: Long Level – Use for taking azimuth measurements of strike and dip.

B: Circular (Bulls Eye) Level – Use for taking angle measurements of dip.

C: Iron Needle – Points to magnetic North and it is damped using the magnet below the pivot point. But the bearing can be adjusted accordingly by rotating the declination zero pin.

D: 360-degree Graduated Circle – Use for azimuth readings that are accurate to half of a degree.

E: 90-degree Dip Circle – Use for measuring dip using the long level on the vernier.

F: Needle Pin – Helps to lock the needle in place in order to take a reading.

G: Vernier – The vernier is used for inclination measurements with an accuracy to 30 minutes.

How to note Strike and Dip

- There are many styles, geologists use to note dip and strike. Sometimes confusing.
- Usual convention is: STRIKE / DIP ANGLE / DIP DIRECTION *[if you follow the right hand rule, you do not have to mention the DIP DIRECTION; adding 90 with the strike will give you dip direction]*
- Strike must be written in 3-digit numbers (e.g., 078, not 78)
- Assume a bedding plane has a strike 120° (measured following right hand rule); dip angle 45°.

120/45

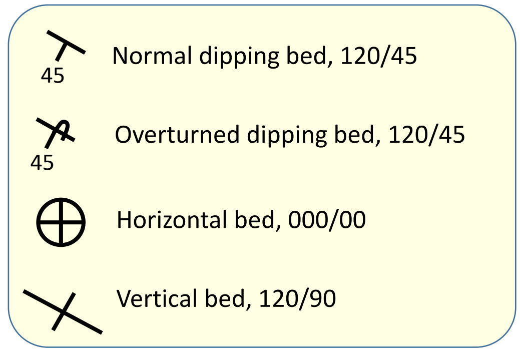
Or,

120/45→210

Or,

120/45 SW

[3-digits/2-digits format]



How to note (write) Trend and Plunge

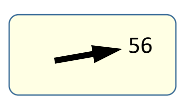
- Fortunately, and unlike dip-strike, geologists follow unique style in mentioning Trend and Plunge.
- Usual convention is: PLUNGE / TREND
- Trend must be written in 3-digit numbers (e.g., 078, not 78)
- Assume a linear element has a trend 080° and plunge 56°.

56/080

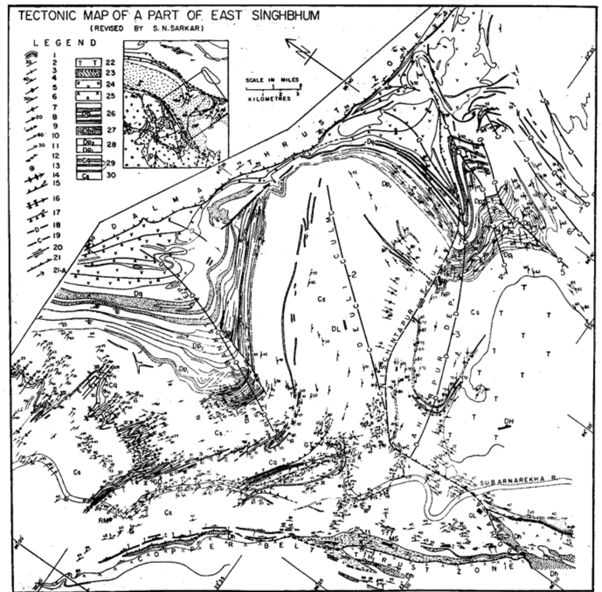
Or,

56 → 080

[2-digits/2-digits format]

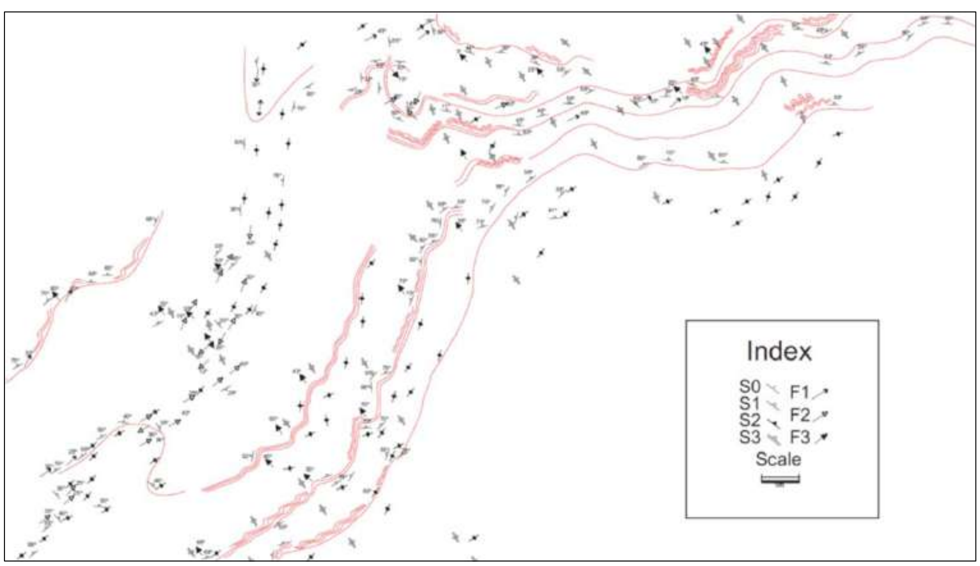


A structural map with measured Structural data



Sarkar, 1962

A structural map with measured Structural data



Next Lecture

Estimating the Deformation: STRAIN

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Experimental Rock Deformation Laboratory

Lecture 18. Concept of Strain

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Aims of this lecture

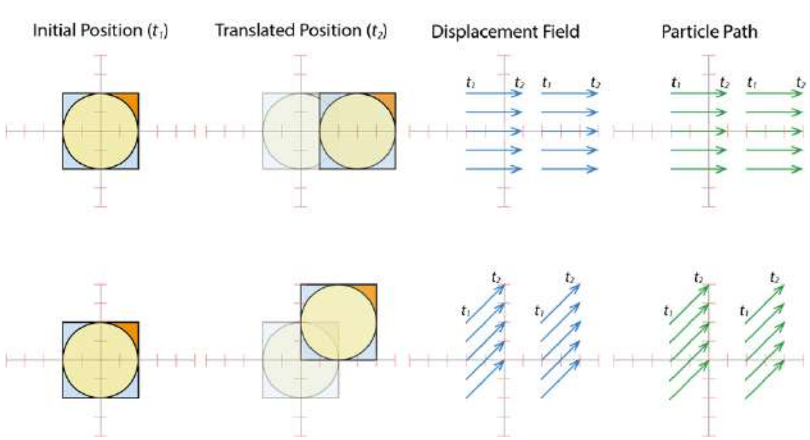
- Overview of Deformation (strain) – displacement, velocity vectors, particle paths
- Homogeneous and Heterogeneous Deformation
- Strain in 1D, 2D and 3D
- Strain Ellipse, Ellipsoid and description
- Coaxial (Pure Shear) and Non-coaxial (Simple Shear) Deformation

What is deformation?

- A change in form and/or shape.
- Deformation is the transformation from an initial to a final geometry by means of rigid body translation, rigid body rotation, distortion and/or volume change (dilation).
- Deformation relates the positions of particles before and after the deformation history, and the positions of points before and after deformation can be connected with vectors – Displacement Vectors.
- The actual path that each particle follows during the deformation history is referred to as Particle Paths.

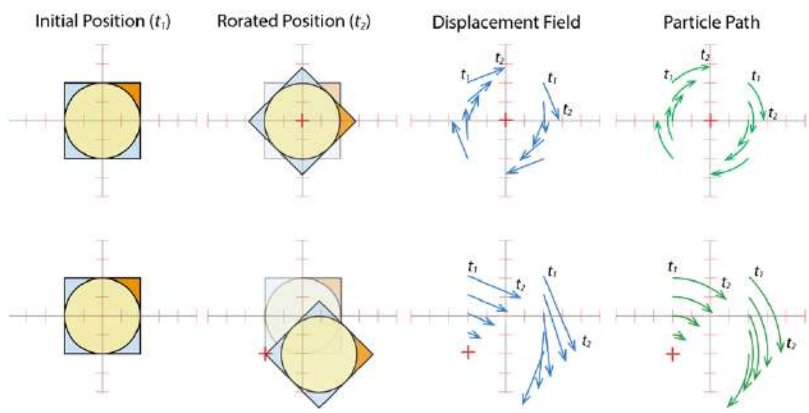
Rigid Body Translation

Rigid Body Translation moves every particle in the rock-mass in the same direction and the same distance. The displacement field consists of parallel vectors of equal length.



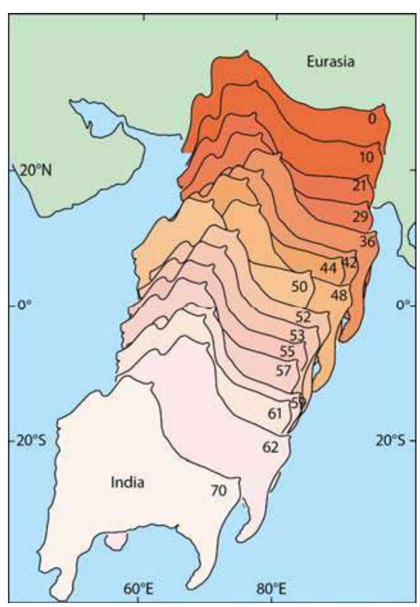
Rigid Body Rotation

Rigid Body Rotation involves a uniform physical rotation of a rock volume relative to an external coordinate system and along a rotation axis (+).



Rigid Body Motion of India

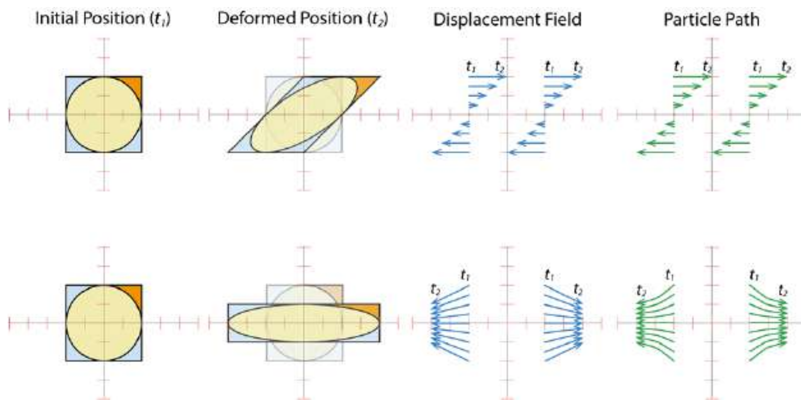
Think of the travel of India from the Southern Hemisphere to its present position.



Patrait & Achache, Nature (1984)

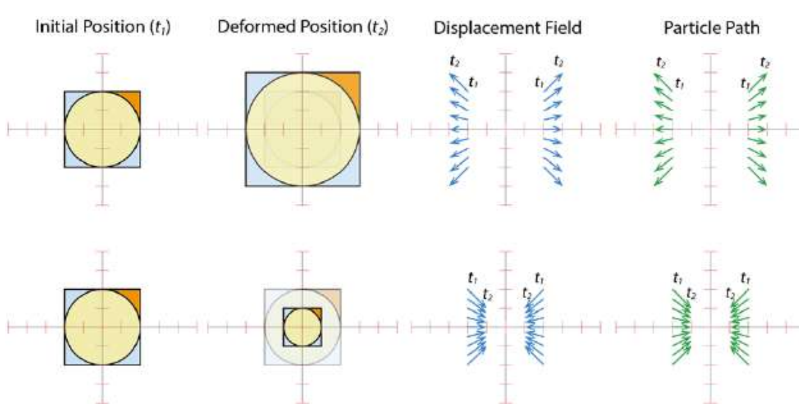
Distortion (Strain) – Constant Volume

Any non-rigid change in shape, without change in volume, is referred to as **Constant Volume Strain**. The particles in a rock have changed positions relative to each other involving either or both Translation and Rotation.



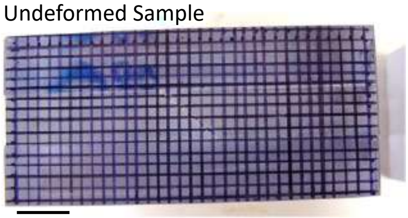
Distortion (Strain) – Volume Deformation

Even if the shape of a rock-mass is unchanged, it may shrink or expand during deformation. We therefore have to add volume change (area change in two dimensions) for a complete description of deformation. Volume change, also referred to as *dilation (positive or negative)*, is commonly considered to be a special type of strain, called **volumetric strain**.



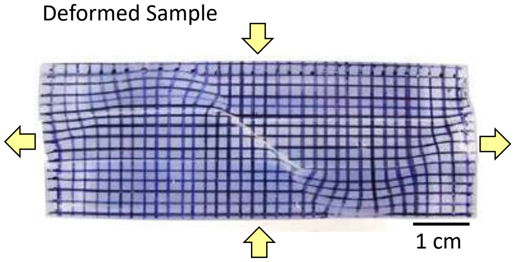
A few examples

Undeformed Sample



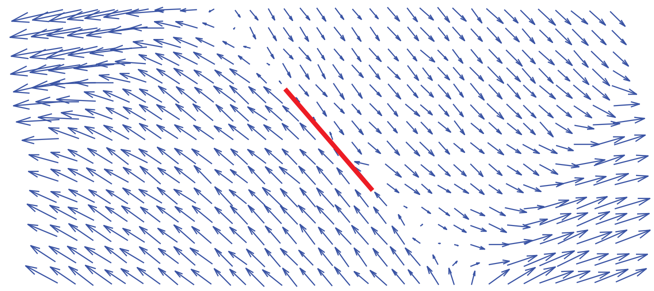
1 cm

Deformed Sample



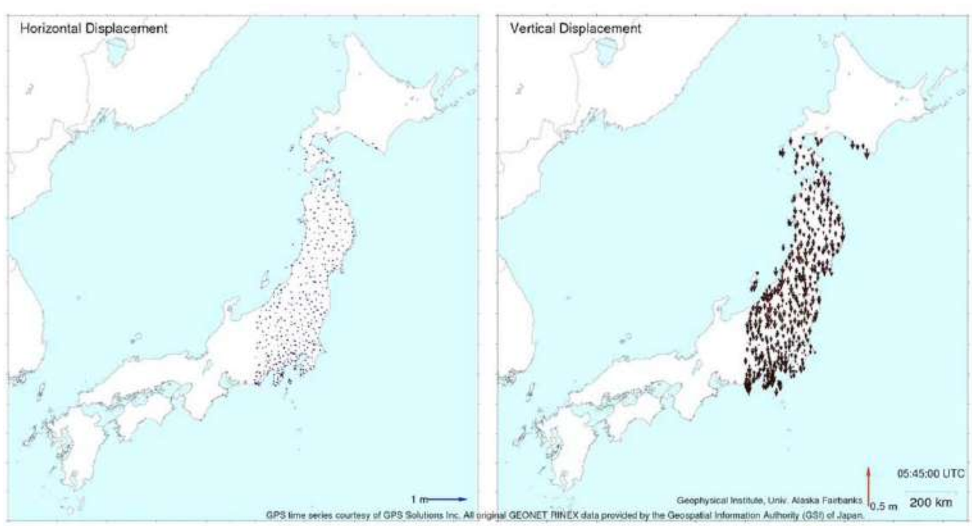
1 cm

Displacement Field



Unpublished experiments: S. Misra

A few examples



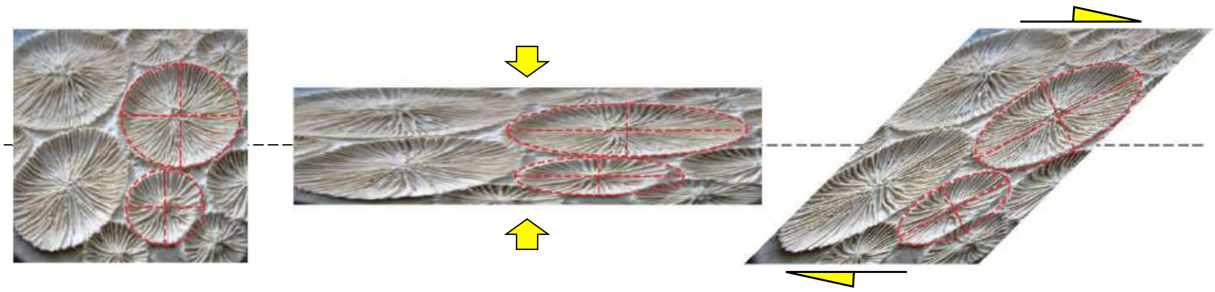
Horizontal and Vertical ground motion of 2011 Tōhoku Earthquake, Japan

Homogeneous Deformation

A given strain may have accumulated in an infinite number of ways.

Where the deformation applied to a rock volume is identical throughout that volume, the deformation is **Homogeneous**. [A circle will change to an ellipse]

For homogeneous deformation, *originally straight and parallel lines will be straight and parallel also after the deformation*. Also, *identically shaped and oriented objects will also be identically shaped and oriented after the deformation.*



Undeformed — Deformed (Pure Shear) — Deformed (Simple Shear)

Heterogeneous (inhomogeneous) Deformation

If the deformation is not homogeneous, it is then Heterogeneous.

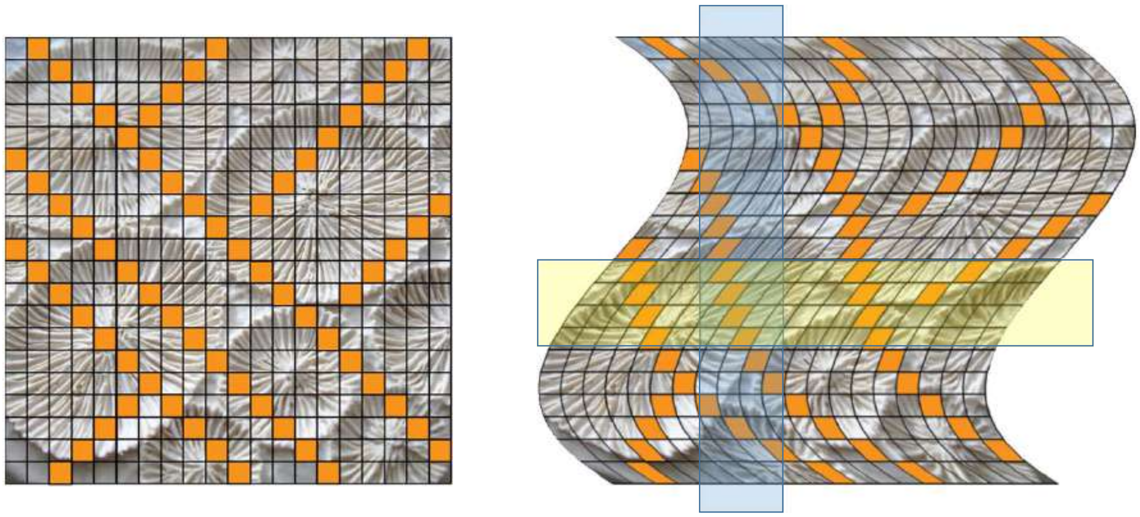
Where the deformation applied to a rock volume is **NOT** identical throughout that volume, the deformation is **Heterogeneous**.

For Heterogeneous deformation, *originally straight and parallel lines will **NOT** be straight and parallel after the deformation*. Also, *identically shaped and oriented objects will also **NOT** be identically shaped and oriented after the deformation.*

Undeformed — Deformed — Deformed

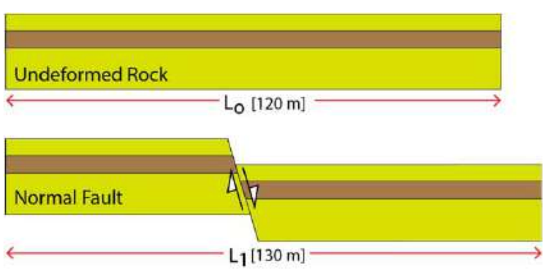
Homogeneous and Heterogeneous Deformation

A deformation that is homogeneous on one scale may be considered heterogeneous on a different scale and direction.



Strain in One Dimension

LINEAR STRAIN



- **Elongation**: the ratio of the change in length to the initial length

$$\varepsilon = (L_1 - L_0)/L_0 = 0.083$$

- **Stretch**: the ratio of deformed and undeformed length

$$s = L_1/L_0 = (1+\varepsilon) = 1.083$$

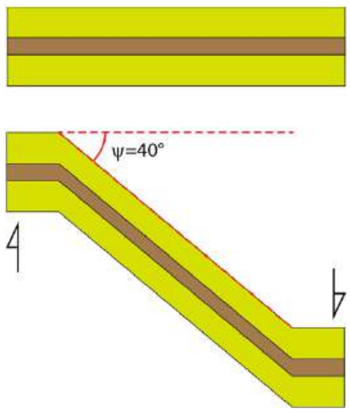
- **Quadratic Elongation**: the square of stretch

$$\lambda = s^2 = (1+\varepsilon)^2 = 1.174$$

These are used for different purposes in strain analysis; however, they are not independent

Strain in One Dimension

ANGULAR STRAIN



Angular shear, ψ, which describes the change in angle between two originally perpendicular lines in a deformed medium.

The shear strain γ is the tangent to the angular shear :

$\gamma = \tan \psi = 0.84$

Strain in Two Dimension

In two dimensions, during homogeneous deformation an imaginary circle on the surface of the deforming rock takes a shape of an ellipse.

The ellipse is known as **Strain Ellipse** and describes the amount of elongation/shortening in any direction in a plane of homogeneous deformation

A circle of unit radius (but it can be of any size) and flattened vertically parallel to the coordinate axis is homogeneously deformed into an ellipse with two major axes which, initially, were diameters of the circle. This **strain ellipse** is a two-dimensional, graphical concept to visualize the amount of ***linear*** and ***angular*** strain involved in the deformation of a rock.

The longest and shortest radii, known as the **Principal Strain Axes,** define the strain ellipse. In the considered coordinate-parallel flattening, these axes are vertical (short) and horizontal (long)

Strain in Two Dimension

Description of Strain Ellipse – Dimension and orientation

One needs only three parameters to describe the strain ellipse – the dimension (short and long) and the orientation of the principal strain axes.

The strain ellipse is conveniently described by a long (X) and a short (Z) axis (the principal strain axes).

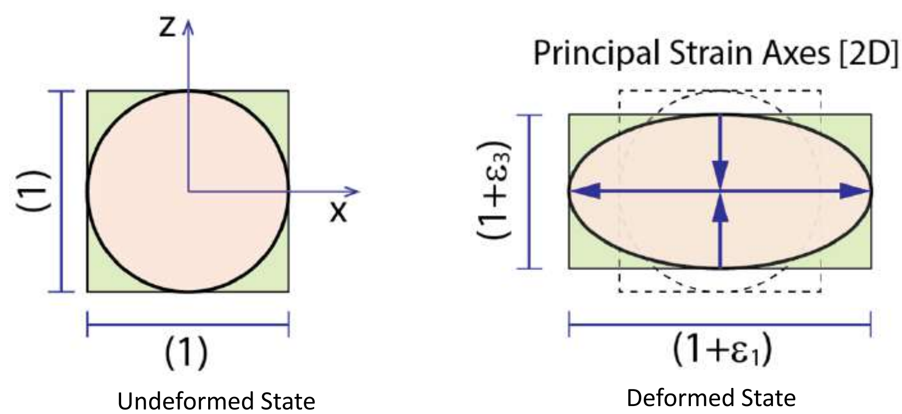
The length of the LONG principal strain axis (stretch axis) : $(1+\varepsilon_1) = \sqrt{\lambda_1}$

The length of the SHORT principal strain axis (shortening axis) : $(1+\varepsilon_3) = \sqrt{\lambda_3}$

The *orientation* is usually the anticlockwise angle between the abscissa and the longest principal strain axis

Strain in Two Dimension

Homogeneous Deformation of a circle into an ellipse with i) no area dilation and ii) no rotation



Strain in three-dimensions

- Strain in three-dimensions is very much analogous to strain in two-dimensions [we need to add *Y*].
- Homogeneous deformation without volume change in three-dimensions can be described as the change in shape of an imaginary or a material sphere.
- The sphere becomes an ellipsoid whose shape and orientation describe the strain. The equation describing this ellipsoid is:

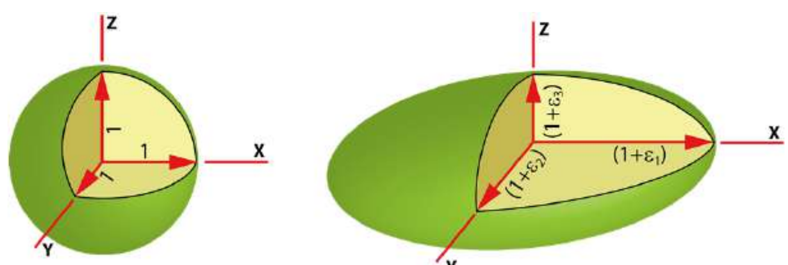
$$\frac{x^2}{(1+\varepsilon_1)^2}+\frac{y^2}{(1+\varepsilon_2)^2}+\frac{z^2}{(1+\varepsilon_3)^2}=1$$

- The three axes of the strain ellipsoid are the maximum (*X*), intermediate (*Y*) and minimum (*Z*) **principal strain axes.** They are also mutually perpendicular to each other.

$X = 1+\varepsilon_1 = \sqrt{\lambda_1}$	$Y = 1+\varepsilon_2 = \sqrt{\lambda_2}$	$Z = 1+\varepsilon_3 = \sqrt{\lambda_3}$
[Stretching axis]	*[Intermediate axis]*	*[Shortening axis]*

Strain in three-dimensions

Homogeneous deformation of a sphere



$X = Y = Z = 1$

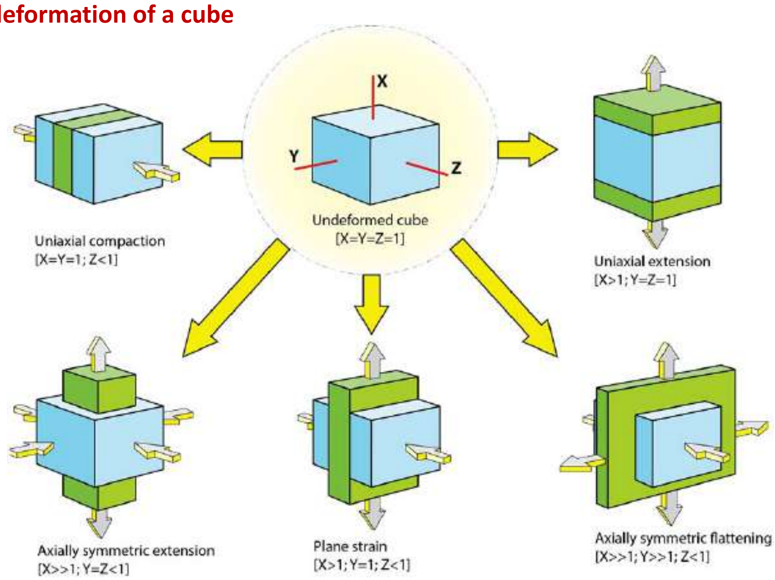
$X = 1+\varepsilon_1 = \sqrt{\lambda_1}$ *[Stretching axis]*

$Y = 1+\varepsilon_2 = \sqrt{\lambda_2}$ *[Intermediate axis]*

$Z = 1+\varepsilon_3 = \sqrt{\lambda_3}$ *[Shortening axis]*

Strain in three-dimensions

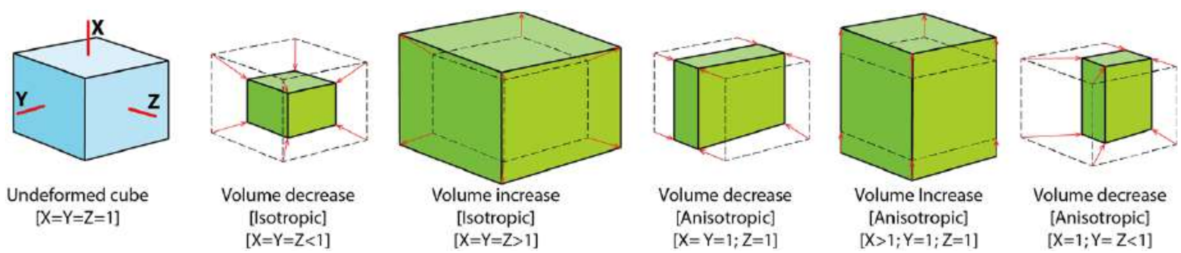
Homogeneous deformation of a cube



Strain in three-dimensions

The Volume Change

- A pure volume change or volumetric strain of an object is given by $\Delta=(V - V_0)/V_0$, where V_0 and V are volumes of the object before and after the deformation, respectively.
- The volume factor Δ is thus negative for volume decrease and positive for volume increase.
- ***Isotropic volume change*** happens when $X=Y=Z>1$ (volume increase) or $X=Y=Z<1$ (volume decrease)
- ***Anisotropic volume change*** happens when $XYZ \neq 1$ (also $X=Y=Z \neq 1$)and two or all of X, Y and Z are different.



Pure and Simple Shear

If we approximate, the overall strain is homogeneous and can be discussed in two dimensions (*plane strain*), where no area dilatation has taken place, then, there are two end members -

PURE SHEAR (coaxial deformation)

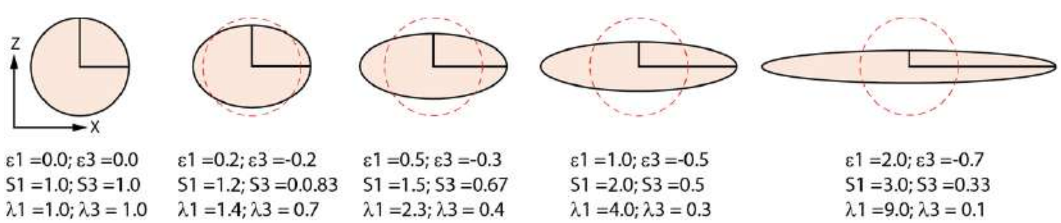
SIMPLE SHEAR (non-coaxial deformation)

The pure and Simple shear are strain regimes and they are the end members to better understand and approximate natural deformation. In nature, ***there is nothing Pure and nothing Simple***.

Strain in Two Dimension

Coaxial Deformation: The principal strain axes remain parallel to the same material lines throughout straining (i.e. the axes of the finite and infinitesimal strain ellipses remain parallel throughout the deformation). The **coaxial** deformation is **irrotational**.

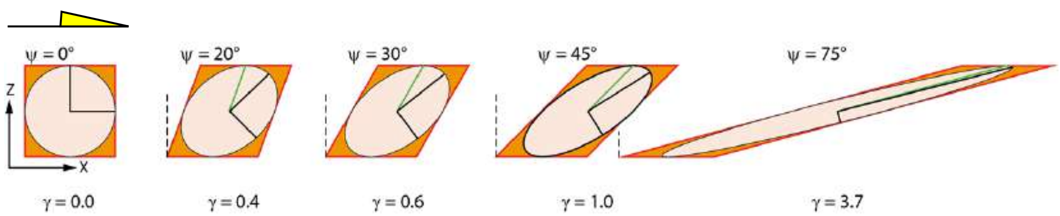
Pure Shear: A constant volume, coaxial and plane strain deformation. *All lines (except the principal strain axes) deflects towards the line of maximum extension*. In that case $(1+\varepsilon_1) = 1 / (1+\varepsilon_3)$.



Strain in Two Dimension

Non-coaxial Deformation: The axes of the finite and infinitesimal strain ellipses are not parallel. Detailed observation reveals that the principal axes of the strain ellipse rotate through different material lines at each infinitesimal strain increment: non-coaxial deformation is **rotational**.

Simple Shear: A constant volume, non-coaxial and plane strain deformation.
A square or rectangle subjected to simple shear changes to a parallelogram. The vertical sides of the square rotate but remain parallel to each other during deformation.



Next Lecture

Basics of Force and Stress

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 19. Concept of Stress

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Concept of Mechanics, Force and Stress, dimensions and units
- Stress on a Surface and at a Point; Stress Tensor
- Stress Ellipse and Ellipsoid
- Compressive, Tensile and Shear stresses

Structural Geology and Mechanics

- We have learnt now that the rock-masses get strained (deformed) and to achieve the strain the rock-mass must have experienced some natural forces/pressures.

- If we consider the rocks are "*materials*", the study of the deformation of rocks under forces falls under the subject "***Mechanics***", which deals the science related to the behaviour of physical materials subjected to force and displacements. *Think of the term we use "Rock Mechanics".*

- Therefore, the study of the deformation of rocks can be included and explained under the broader subject: ***MECHANICS.***

Concept of Continuum

- A body is and remains CONTINUOUS under the action of external forces
  - Consisting of continuous material points
  - Neighboring points remain neighbors
  - Neglecting its atomistic structure

CONTINUUM MECHANICS

- A continuum, or continuous medium, is represented as a continuous aggregates of idealized material particles (elemental volumes). They are small enough that their position can be given in terms of points in some co-ordinate systems, yet large enough that local value of any variable does not depend on fluctuations at the atomic scale in the immediate neighbourhood of the point.

- In order to deal with the properties and mechanics of continuum, it is therefore necessary to refer the body to *a system of co-ordinates*.

Force

- An object, in motion or in equilibrium is a function of the object's mechanical interaction with the other objects. FORCE is the quantitative measure and description of the mechanical interaction.

- A **force** is a *vector quantity* [*first-order tensor*] and has magnitude, direction and point of application

- SI unit of Force is **Newton** [1Newton is required to accelerate a 1kg mass at 1 meter/second^2] ……[$\boldsymbol{mlt^{-2}}$]

  Dyne [1Dyne is required to accelerate a 1gm mass at 1 cm/second^2]

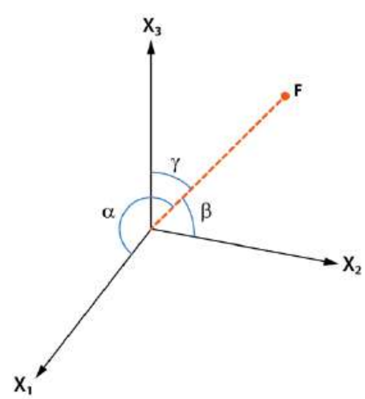
Force

Being a vector, the components of the Force (***F:*** magnitude *F, and* α, β, γ *are the angles it makes with the axes of a Cartesian coordinate system*) in 3D:

$$F_{X_1} = F\cos\alpha \qquad F_{X_2} = F\cos\beta \qquad F_{X_3} = F\cos\gamma$$

and

$$F^2 = F_{X_1}^2 + F_{X_2}^2 + F_{X_3}^2$$



Force

- The forces acting on a body can be divided into two groups:
  - ***Internal forces:*** Internal forces represent the interaction between the particles in the body.
  - ***External forces:*** refer to the action of other bodies on the particles of a given body.

Body forces act on unit mass or unit volume of the body (e.g., gravity and magnetic forces).

Surface forces act on the surface of a body when it comes in contact with another body. The surface forces are mostly responsible for the deformation of rocks at various scales. *The surface forces acting on an area are often referred as traction*.

Stress on a surface - TRACTION

- The stress on a surface (traction) can be idealised in geological context in many different ways: on a fault plane, on the contact areas between adjacent grains, meteoritic impacts etc.
- In mechanics, the stress on a surface (traction, T) is defined as the ratio between the Reactive Force (F) and the Surface area (S), on which the force is acting.

$$\vec{T} = \frac{\vec{F}}{S}$$

- As, Force is a vector, the Stress on a surface (traction) is also a vector.
- SI unit of Stress is **Pascal (Pa)** = Newton/(Meter)^2 = 1 kg/m.s^2 ……[$\boldsymbol{ml^{-1}t^{-2}}$]

1 Pa = 10^{-5} bar = 0.000145 psi 1 MPa = 10 bar = 145 psi

Pressures in normal bicycle and car tyres are 0.6 and 0.24 MPa, respectively. Lithostatic Pressures at the lower-upper mantle boundary (670 km) ~28 GPa; at core-mantle boundary 330 GPa and at the center of the earth ~400 GPa.

Stress on a surface element

- ***Stress acting on a SURFACE:*** VECTOR (Traction)
- ***Stress acting at a POINT:*** TENSOR

To know more about this and the derivations, see here:

https://youtu.be/rKafI2wUgJ8?list=PLHyuArGIlyyR_2mObwQ3yng18LDnDqidp

Stress at a point – STRESS TENSOR

- For easier mathematical operations, imagine a very small parallelepiped around the ***P*** with dimensions ΔX_1, ΔX_2 and ΔX_3.
- The Tractions of the three positive faces of the parallelepiped can be resolved into their Cartesian components: one normal, and two tangential to the face on which the tractions acts.

$T_{(1)i} = (\sigma_{11}, \tau_{12}, \tau_{13})$ ⇨ Face normal to X_1

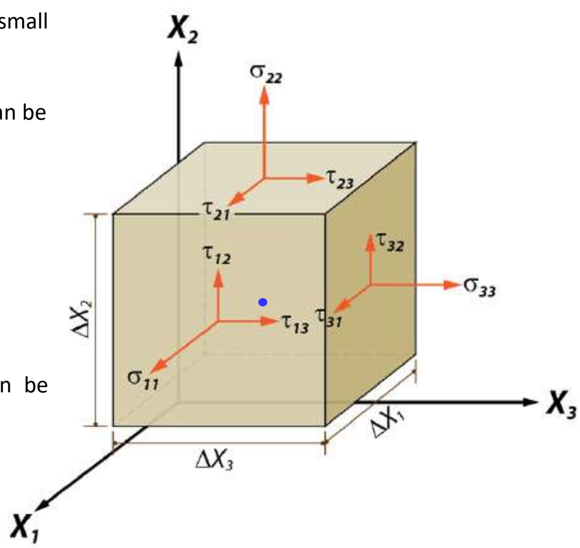
$T_{(2)i} = (\tau_{21}, \sigma_{22}, \tau_{23})$ ⇨ Face normal to X_2

$T_{(3)i} = (\tau_{31}, \tau_{32}, \sigma_{33})$ ⇨ Face normal to X_3

- The nine components of the tractions acting at a point can be expressed in index notation:

$$\sigma_{ij} = \begin{bmatrix} \sigma_{11} & \tau_{12} & \tau_{13} \\ \tau_{21} & \sigma_{22} & \tau_{23} \\ \tau_{31} & \tau_{32} & \sigma_{33} \end{bmatrix}$$

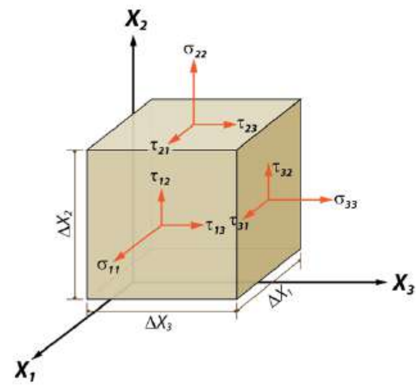
STRESS TENSOR



Stress at a point - Equilibrium

- The Conditions of equilibrium for *body and surface forces*

$$\left.\begin{aligned}
\frac{\partial\sigma_{11}}{\partial x_1}+\frac{\partial\sigma_{21}}{\partial x_2}+\frac{\partial\sigma_{31}}{\partial x_3}+\rho\boldsymbol{X}_1=0\\
\frac{\partial\sigma_{12}}{\partial x_1}+\frac{\partial\sigma_{22}}{\partial x_2}+\frac{\partial\sigma_{32}}{\partial x_3}+\rho\boldsymbol{X}_2=0\\
\frac{\partial\sigma_{13}}{\partial x_1}+\frac{\partial\sigma_{23}}{\partial x_2}+\frac{\partial\sigma_{33}}{\partial x_3}+\rho\boldsymbol{X}_3=0
\end{aligned}\right\} \quad \frac{\partial\sigma_{ji}}{\partial x_j}+\rho\boldsymbol{X}_i=0$$

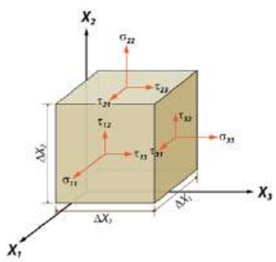


- The Conditions of equilibrium for *moments*

$$\sigma_{ij}=\sigma_{ji} \quad \Longrightarrow \quad \frac{\partial\sigma_{ji}}{\partial x_j}+\rho\boldsymbol{X}_i=0;\frac{\partial\sigma_{ij}}{\partial x_j}+\rho\boldsymbol{X}_i=0$$

Check the derivations in Ghosh's book (Chapter 5)

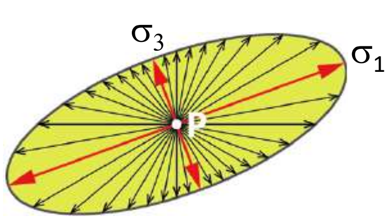
Stress Ellipse and Stress Ellipsoid



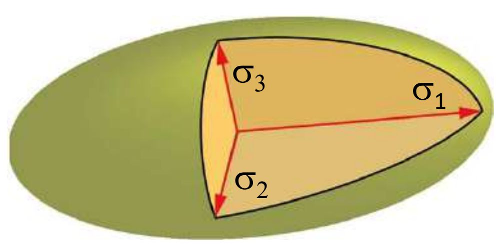
$$\sigma_{ij}=\begin{bmatrix}\sigma_{11} & \tau_{13}\\ \tau_{31} & \sigma_{33}\end{bmatrix}$$

$$\sigma_{ij}=\begin{bmatrix}\sigma_{11} & \tau_{12} & \tau_{13}\\ \tau_{21} & \sigma_{22} & \tau_{23}\\ \tau_{31} & \tau_{32} & \sigma_{33}\end{bmatrix}$$

Different pairs of planes would have different magnitude of stress vectors – when resolved around the point, it would produce an ellipse (2D) or ellipsoid (3D)



2D

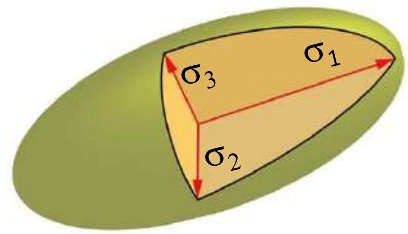


3D

Stress Ellipse and Stress Ellipsoid

- The geometric disposition of the stress ellipsoid (shape and orientation) *reveals the state of stress at a given point* in a rock-mass deforming or even in static-state.

- The largest, smallest and intermediate magnitudes (σ_1, σ_3, and σ_2 respectively) of the stress ellipsoid are known as **Principal Stress** *(eigenvalues)* of Stress of the stress ellipsoid, and the directions as **Principal Axes** *(eigenvectors)* of the stress ellipsoid.



Please remember, the stress and strain ellipsoids (and ellipses in 2D) are very similar physically and mathematically. However, they are different. **(A)** A stress ellipsoid may not lead to a strain ellipsoid (i.e., rocks are nor deforming); **(B)** The shape and orientation of the strain ellipsoid may be very different to those of a stress ellipsoid responsible for the strain.

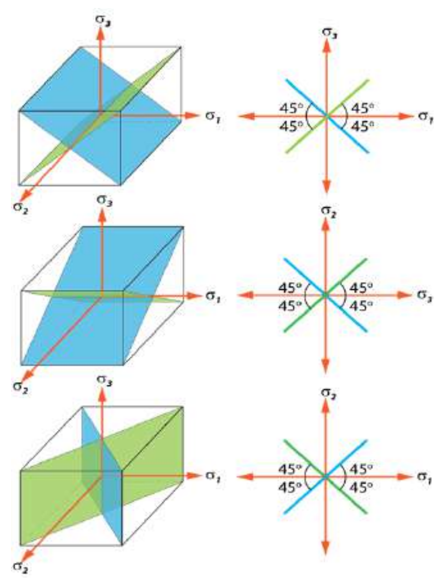
Maximum shear stresses and their orientations

The principal shearing stresses act on the following planes

1. A pair of planes intersecting along the σ_2 axis and inclined at ±45° with the σ_1 or the σ_3 axis; the absolute value of the shear stress on these planes is the greatest and has the value $\tau_2 = \pm\frac{1}{2}(\sigma_3 - \sigma_1)$.

2. A pair of planes intersecting along the σ_1 axis and inclined at + 45° with the σ_2 or σ_3 axis; the shear stress on these planes is $\tau_1 = \pm\frac{1}{2}(\sigma_2 - \sigma_3)$.

3. A pair of planes intersecting along the σ_3 axis and inclined at ±45° with the σ_1 or σ_2-axis; the shear stress on these planes is $\tau_3 = \pm\frac{1}{2}(\sigma_1 - \sigma_2)$.



Maximum shear stress and orientation

Photo: Romain Plateaux

Maximum shear stress and orientation

Photo: AGU Blog

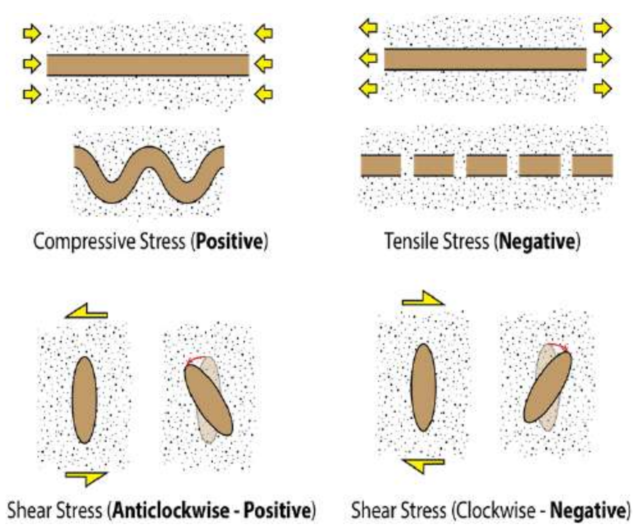
Photo: Santanu Misra

Maximum shear stress and orientation

Photo: GNS Science, NZ

Sign convention of Stress Axes

- **Compressive Stress**: The stress on rock-mass which tends to shrink/shorten the material along the direction of stress (e.g., folding, thrust-faults).
- **Tensile Stress**: The stress on rock-mass which tends to extend the material along the direction of stress (e.g., boudinage, normal-faults).
- **Shear Stress**: The stress on rock-mass which acts along / parallel to the surface (e.g., stress along fault-planes).



Additional Lectures

https://youtu.be/mP0ZT2fmzEM?list=PLHyuArGIIyyR_2mObwQ3yng18LDnDqidp

Next Lecture

Geological Structures

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 20. Break or Flow.. how does a rock deform?

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Brittle, Ductile and Brittle-Ductile deformation
- Rheology – Elastic, Viscous and Plastic
- A couple of examples

Brittle; Ductile and Brittle-Ductile

- Cohesion *ability (stress) to hold particles together in static condition*
- Friction *resistive force develops between two adjacent particles/surfaces due to stress*

Brittle: The rocks must have lost its cohesion to produce joints, cracks, fractures faults (low PT phenomenon)

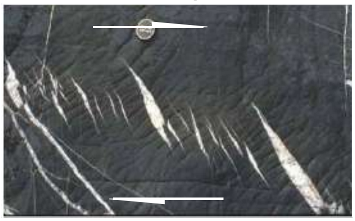
Ductile: The rocks do not loose cohesion but flow (high PT phenomenon)

Brittle-Ductile: Show both brittle and ductile deformation (intermediate PT phenomenon)

These are observation based and essentially scale dependent

Brittle; Ductile and Brittle-Ductile

Brittle regime

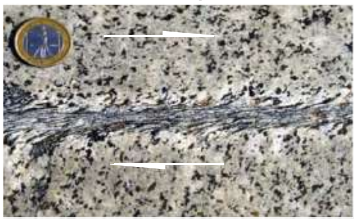


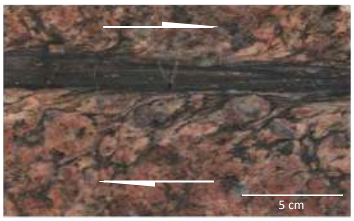
...high concentration of shear fractures, cracks representing localized *brittle* deformation

Brittle-ductile regime

...both ductile and brittle features; developed either simultaneously or sequentially

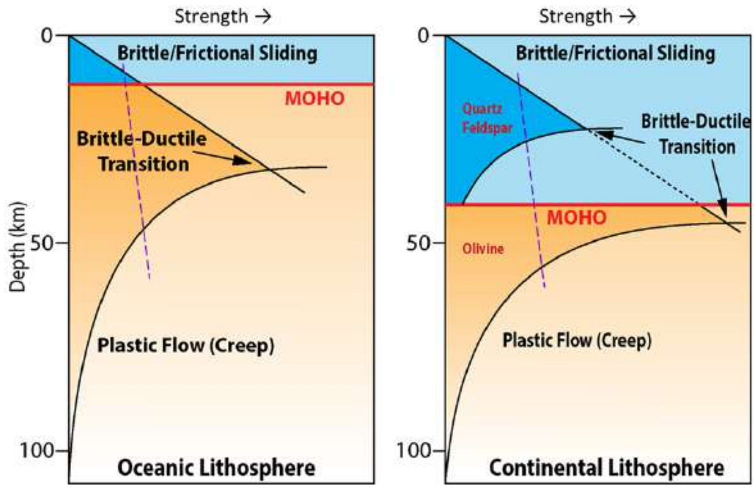
Ductile regime





...structural fabrics, (*e.g.* schistosity) contrasting to the surroundings, indicating localization of intense penetrative *ductile* strain

Brittle; Ductile and Brittle-Ductile



Basics and Definitions

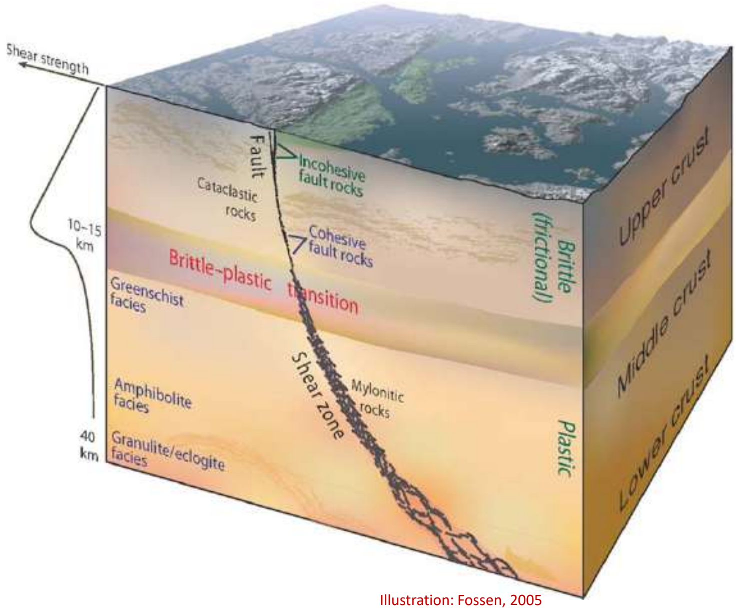


Illustration: Fossen, 2005

Simplified model of the connection between faults, which normally form in the upper crust, and classic ductile shear zones. The transition is gradual and known as the brittle–ductile transition.

The depth depends on the temperature gradient and the mineralogy of the crust. For granitic rocks it normally occurs in the range of 10–15 km.

Rheology

We have learnt "Strain" and "Stress". It is high time now to ask the question, are they related to each other? If yes, how and what is/are the controlling parameter(s) in this relationship?
--- The answer is given in the subject, called **RHEOLOGY**.

The study of the behaviour (flow) of materials under deformation. Rheology ~ *ρει – **flow** in Greek*.

The different deformational responses to applied stress depend on the physical properties of the material under consideration and on external parameters (pressure, temperature and time).

Speaking about "FLOW"

- ***Solid*** and ***Fluid***, in Rheology do not correspond to the definitions based on atomic structures of the materials.
- A material is fluid, independently on its atomic structure, when it flows under constant stress (and under certain conditions).

Think how all the materials, we are all familiar with, will flow along a uniformly polished inclined plane in room condition, only under the effect of gravity….

Water	Syrup
Cooking oil	Honey
Raw Glycerine	Tar oil
Wall-paint	Asphalt
Tomato Ketchup	Glass

Rheology - classification

- Like all other materials, studied under continuum mechanics, can be described to respond to stress by three fundamentally different end members -

Elastic Rheology	Recoverable
Viscous Rheology **Plastic Rheology**	Non-recoverable

Note: The rheology is a large topic and almost all subjects deal with this topic. You will get only a glimpse here. For advanced learning, contact me separately.

Elastic Rheology

- Stress is linearly proportional to strain and the later is fully recoverable (*Hooke's Law*)

This linear relationship is expressed as: $\sigma = E\varepsilon$

E is known as **Young's modulus** or the **Elastic modulus** (also denoted Y) or the stiffness of a material, defined as the slope of the stress-strain curve. Hooke's law is a constitutive equation for elastic materials. Physically, ***E*** quantified, how hard a rock is to deform elastically.

Viscous Rheology

- Fluids, in general, has a resistance to flow under stress. The quantification of the resistance of a fluid to flow is knows as **VISCOSITY** (η) [or, coefficient of viscosity]. Greater the viscosity value, higher is the resistance to flow.

- A perfectly (ideal) viscous material flows like a fluid when influenced by an external force. This means that there is no elastic deformation involved.

- This deformation behaviour at constant volume (*Newtonian Fluid*) is idealised by a **linear viscous constitutive** equation.

Plastic Rheology

- Under some natural conditions the strain-response of rocks cannot be explained neither by elastic nor by viscous rheology.

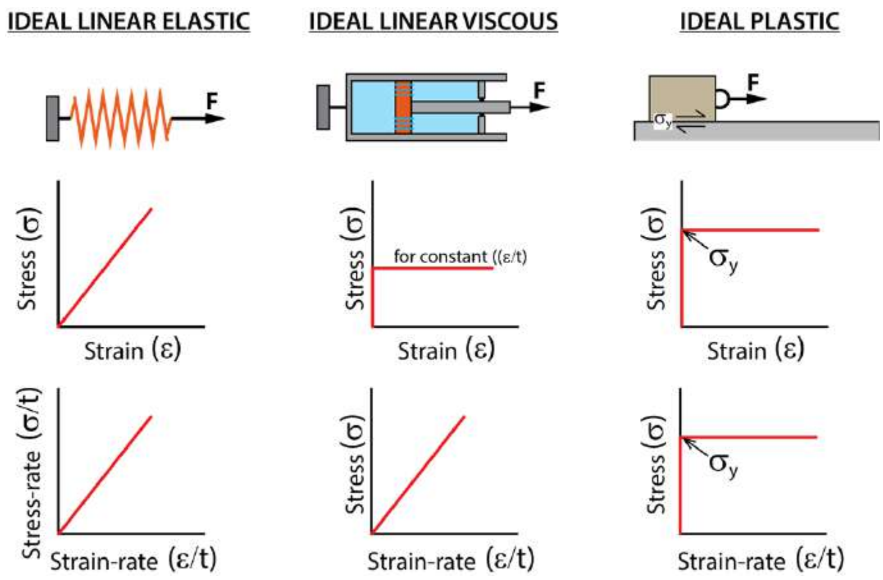
- These materials, during deformation, initially display an elastic behaviour; however, they flow readily at or little above the Yield Stress.

- This typical behaviour of materials under stress is best described the **PLASTIC** Rheology.

- Plastic Rheology is a description of a material behavior under stress to undergo irreversible (permanent) deformation after yield strength (elastic limit) of the material.

- During the the post yield deformation, the rocks must maintain its continuity (cohesion) and should not produce fracture at the scale of observation.

Summary of Rheology Basics



Review of the terminologies

- Brittle
- Ductile
- Brittle - Ductile

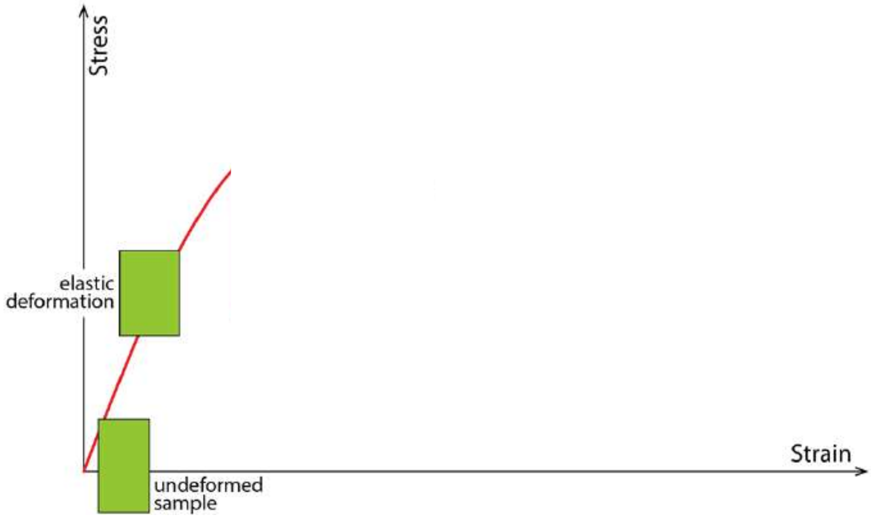
TYPES OF DEFORMATION

- Elastic
- Viscous
- Plastic

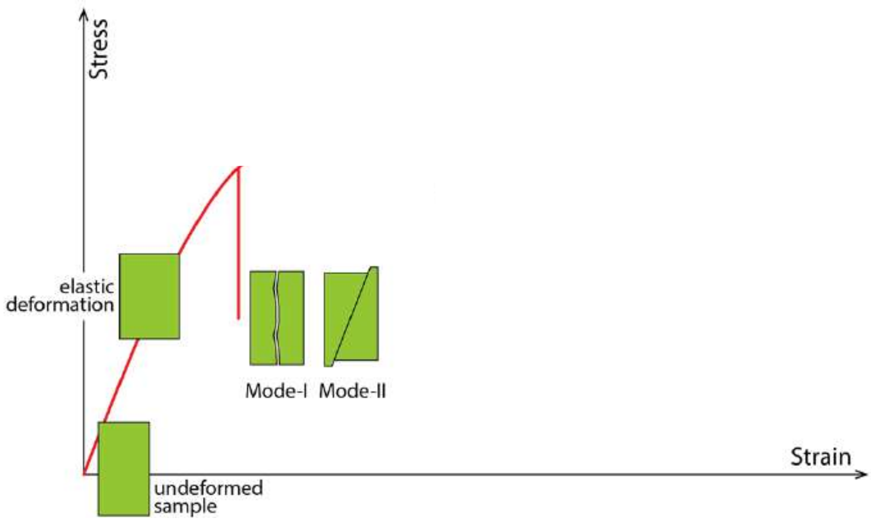
FLOW / MECHANISMS OF DEFORMATION (RHEOLOGY)

Brittle deformation is always **Plastic,** whereas, **Ductile** deformation includes everything which are *not* **Elastic** and **Brittle.**

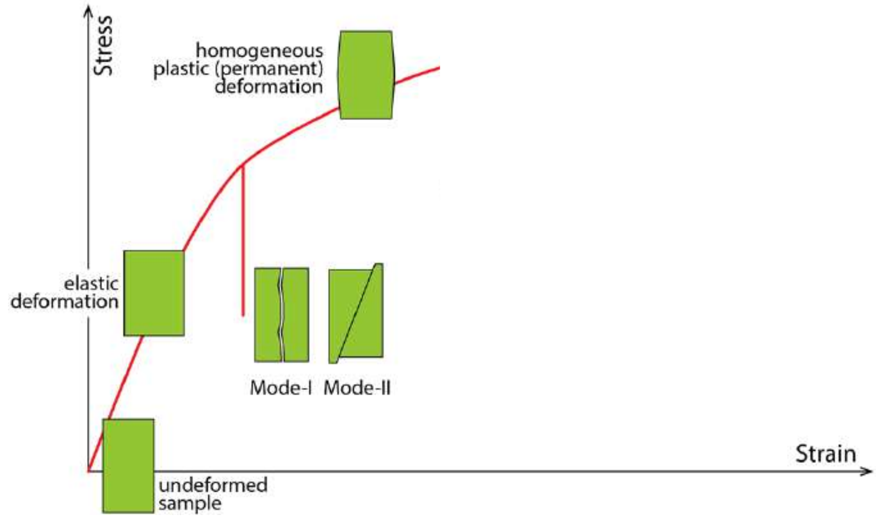
Brittle; Ductile and Brittle-Ductile



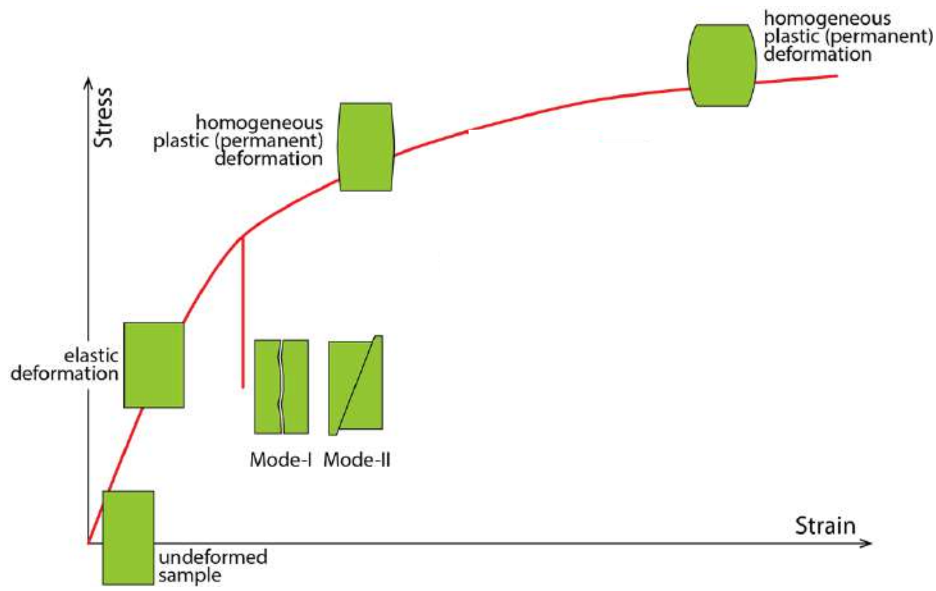
Concept of Localized deformation



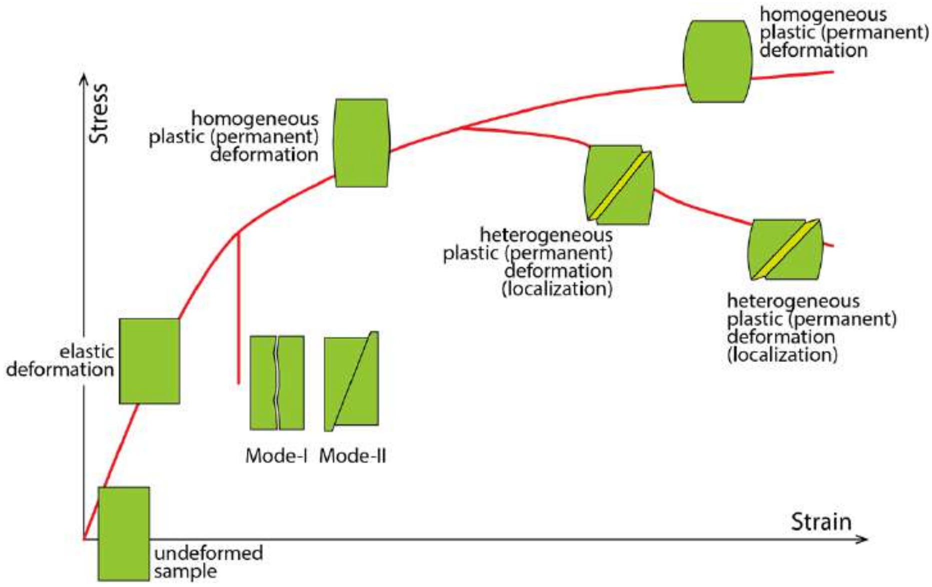
Concept of Localized deformation



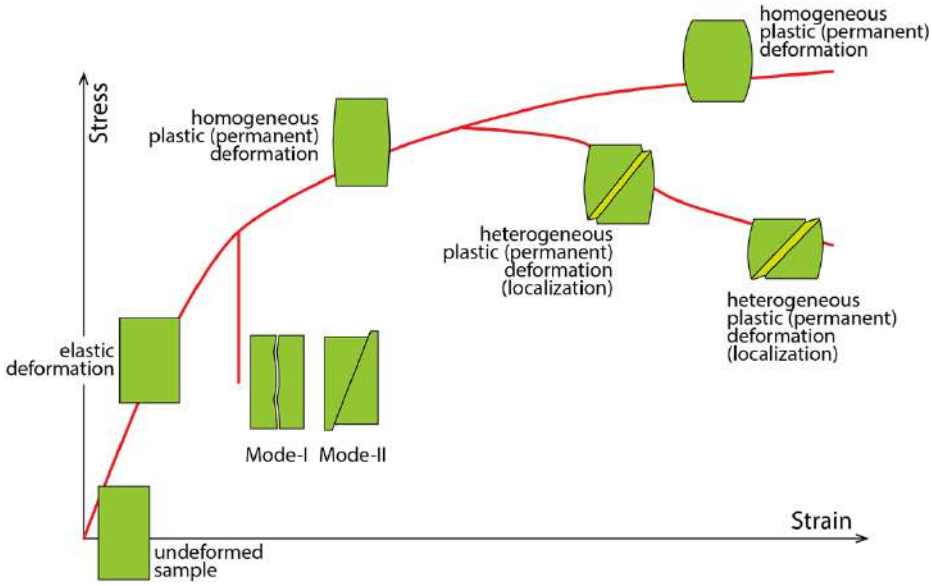
Concept of Localized deformation



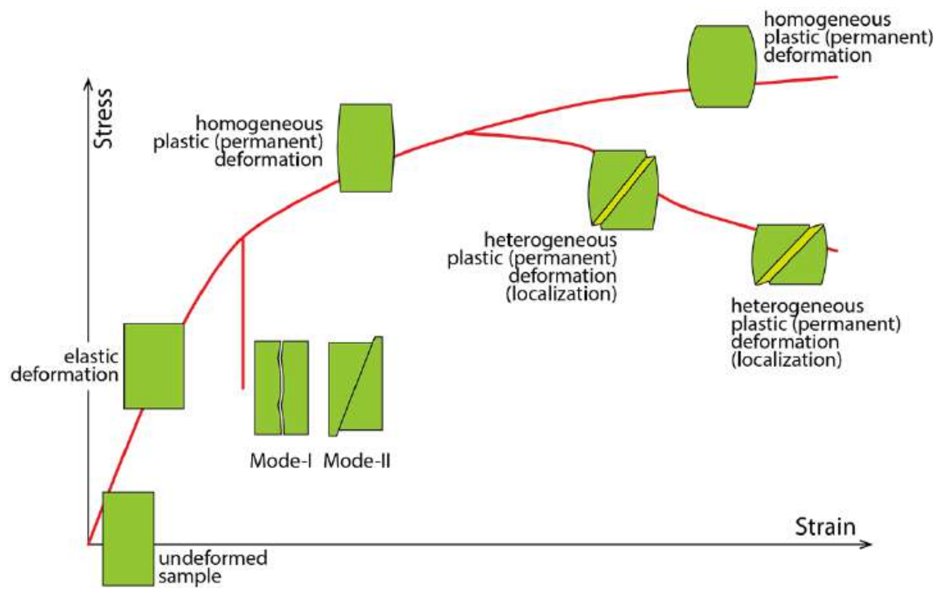
Concept of Localized deformation



Concept of Localized deformation



Concept of Localized deformation



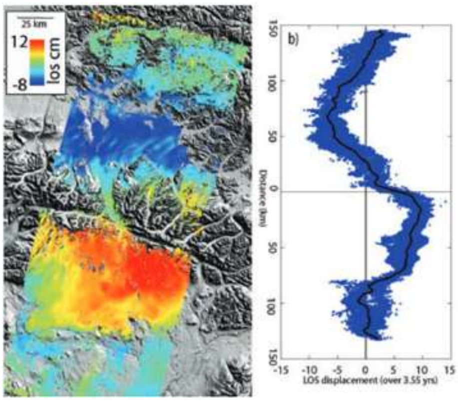
Combined rheology

Rheology of rocks as combined viscous and elastic (visco-elastic).

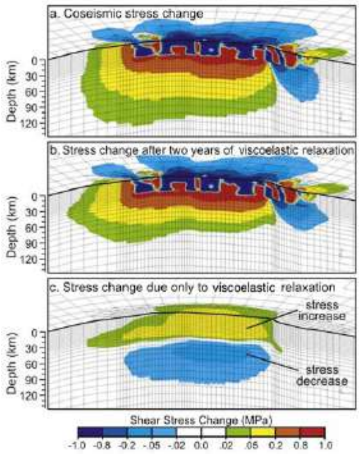
Rheology of rocks as combined elastic and plastic (elasto-plastic).

Rheology of rocks as viscous and plastic (visco-plastic).

Example I: 2002 Denali Earthquake (M 7.9)



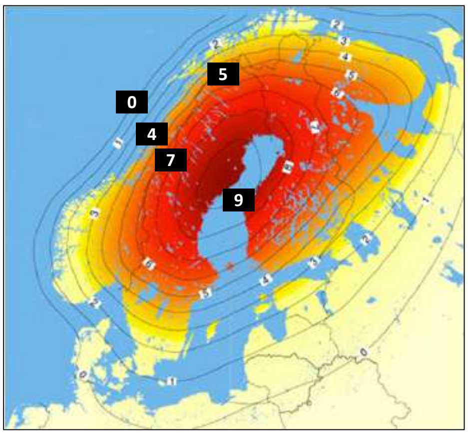
The Denali Fault and the peak displacements [*Briggs et al., 2009, GJI*]



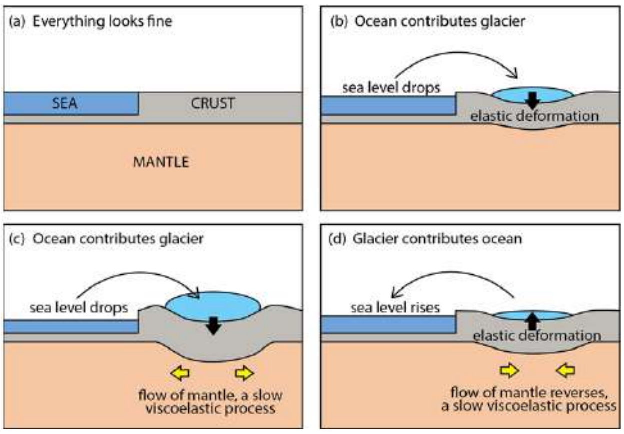
Calculated (a) coseismic, (b) postseismic,and (c) the difference (postseismic minus coseismic)shear stresses (planes parallel to fault surface [*Freed et al., 2006, JGR Solid Earth*]

Example II: Rebound due to deglaciation

A part of Scandinavia is not afraid of Sea-Level Rise !! The observations suggest the sea level here is rising like all other places; the land is rising faster.



land uplift (mm/yr) relative to the centre of the Earth



www.maanmittauslaitos.fi

Next Lecture

Basic Structures and related terminologies
(Fault, Fold and Shear Zones)

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 21. Brittle Structures

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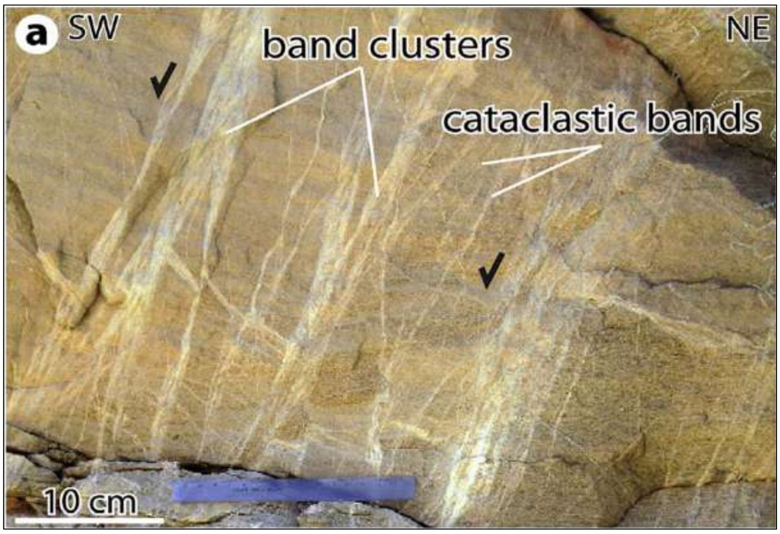
Experimental Rock Deformation Laboratory

Brittle Deformation

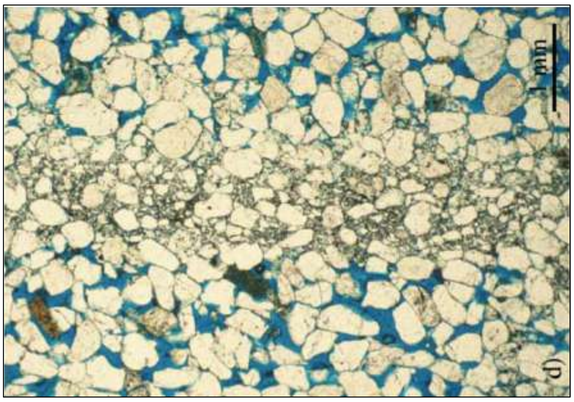
- Combination of brittle fracture and frictional sliding of grains
- Activated when the shear / tensile strength of the rock is exceeded
- A mechanism of low temperature
- No internal distortion of crystal/lattice structures
- Pressure sensitive deformation
- Commonly observed in upper crust
- Characterized by Fracturing at any scale

Compaction Band

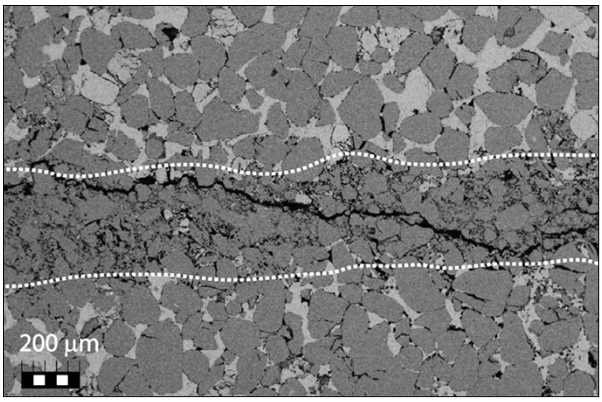


Ballas et al., 2015

Compaction Band

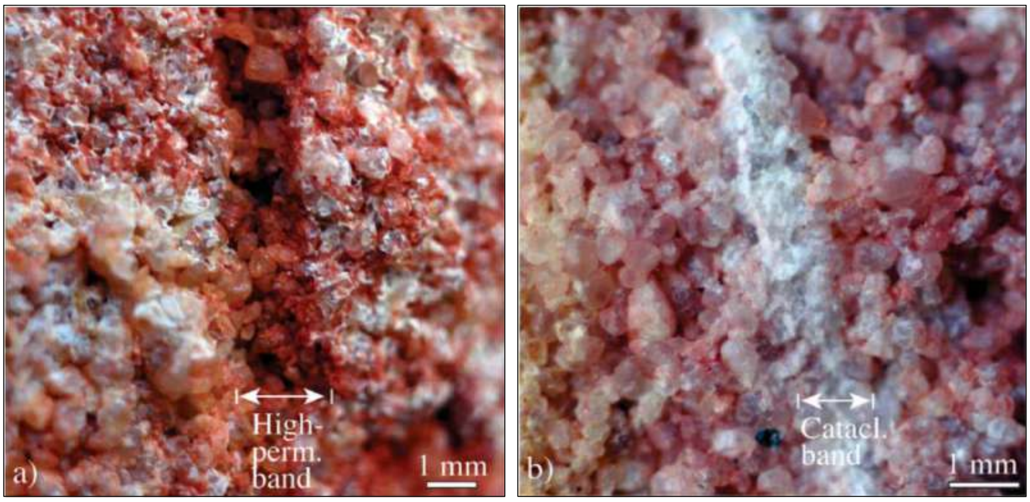


Fossen et al., 2014



Skurtveit et al., 2014

Compaction Band



Fossen et al., 2007

Brittle Failure Criteria

- During brittle fracturing, rocks can deform either by creating new fractures or by can deform along pre-existing fractures. In both cases friction plays an important role.
- Brittle fracturing is commonly described with the **Mohr-Coulomb criterion**.

$$\tau_c = S + \mu(\sigma_n - P_f)$$

τ_c = critical shear stress for fracturing
S = cohesion of the material
μ = co-efficient of friction
σ_n = normal stress acting on the fracture surface
P_f = pore fluid pressure

- If the there is any pre-existing fracture in the rock, the rock has no cohesion and S = 0 (*Amontons Law*).

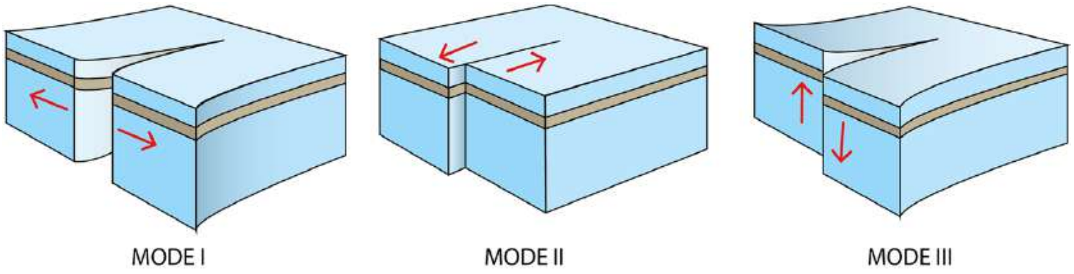
Note: The Mohr-Coulomb criterion describes only a critical state of stress, at which fracturing occurs. It does not place a relationship between stress and strain and is therefore not a constitutive relationship of rheology (flow law)

Types of Fractures

Mode I: Opening mode (a tensile stress acting normal to the plane of the crack)

Mode II: Sliding mode (a shear stress acting parallel to the plane of the crack and perpendicular to the crack front)

Mode III: Tearing mode (a shear stress acting parallel to the plane of the crack and parallel to the crack front)

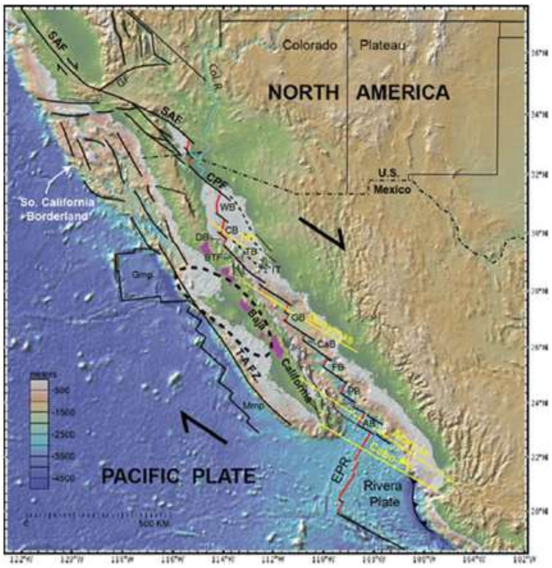


Mode I Fractures

https://geologictimepics.com

Iceland's rift valley in Thingvelir, marks the crest of the Mid-Atlantic Ridge

Mode II Fractures



http://geoprisms.org

Some typical Mode I structures

Joints

Veins and dikes

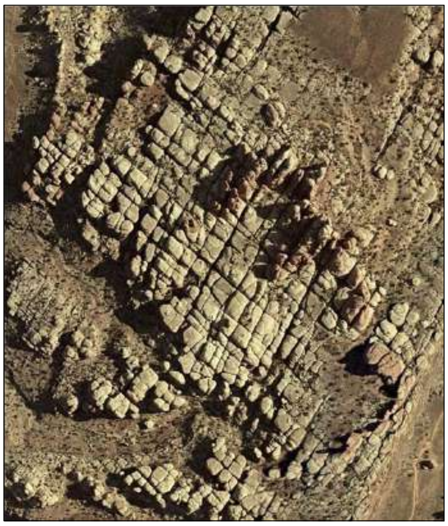
Boudinage and Pinch-and-Swell (*ductile*)

Joints

- Joints (Mode-I fractures) are planes of separation on which no or undetectable shear displacement has taken place. The two **walls** maintain tiny opening (*aperture*) and typically remain in tight (matching) contact.
- Joints from due to
  - regional tectonics (i.e. the compressive stresses in front of a mountain belt),
  - folding (due to curvature of bedding),
  - faulting, or
  - internal stress release during uplift or cooling.
- The growth of Joints is controlled by the thickness of the deforming rock. Apertures can be open (resulting in permeability enhancement) or occluded by mineral cement (resulting in permeability reduction). A joint with a large aperture (> few mm) is a **fissure**.
- If present in sufficient number, open joints may provide adequate porosity and permeability in an otherwise impermeable rock - > a productive **fractured reservoir**.

Set of Joints


http://whattherockstellus.blogspot.com


https://structuralgeo.files.wordpress.com

Set of Joints

Photograph: Santanu Misra

Veins and Dikes

A dike (also dyke), is a sheet of rock that is formed in a fracture of a pre-existing rock body.

Dikes can be either magmatic or sedimentary in origin.

Magmatic dikes form when magma flows into a crack then solidifies as a sheet intrusion, either cutting across layers of rock or through a contiguous mass of rock.

Clastic dikes are formed when sediment fills a pre-existing crack

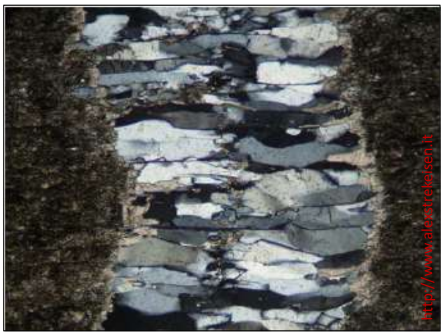
diabase dike intrusions

An igneous intrusion cut by a pegmatite dyke, which in turn is cut by a dolerite dyke (Koster Islands in Sweden)

Veins and Dikes

Veins in rocks are practically the same as dikes; yet a distinction is sometimes made that dikes are narrow, often straight-walled and run for considerable distances, while veins are irregular, discontinuous and of limited extent.

Extension fractures



Quartz vein in shale; width of the image: 2mm

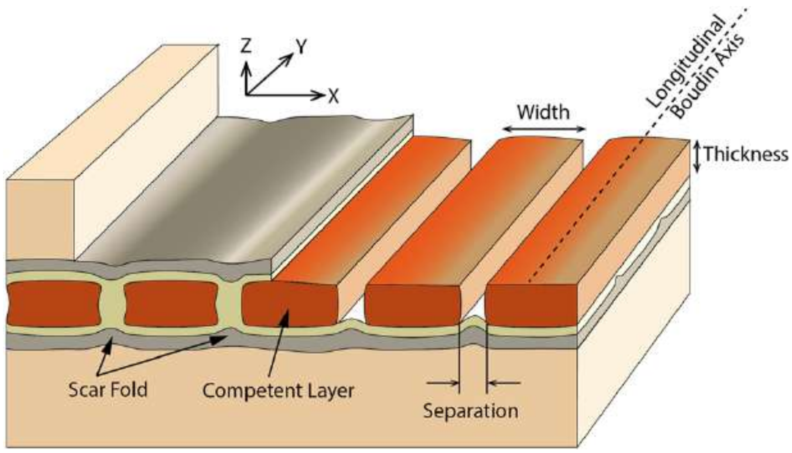
Boudinage

Marble with pelitic boudinaged layers
[Width of the image: ~ 50cm]

Boudinaged allanite crystal.
Width of the image: 7mm

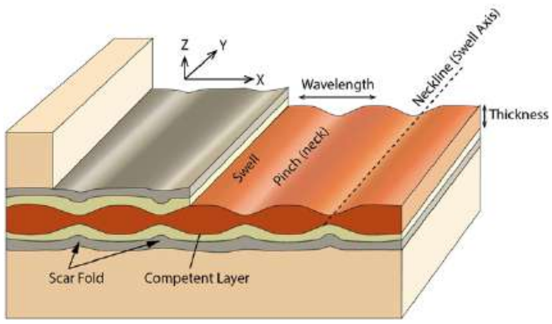
Boudinage

- Stretching, necking and eventually segmentation of a layered body surrounded by a less competent (i.e., more deformable) matrix develops side by side, sausage-shaped bodies, the ***boudins***. A structure found in low grade metamorphic rocks.



Pinch-and-swell Structure

- At higher grades, and sometimes in unconsolidated rocks, the competent layers have generally not broken through; narrow, thinned necks separate and alternate with boudins of relatively still, thick layers. The resulting structure is called ***pinch-and-swell***.



- After separation, the disconnected layer segments display lens- or pillow-shaped forms. Extreme stretching reduces necks to very thin and long selvage of the layer connecting variably shaped swells.

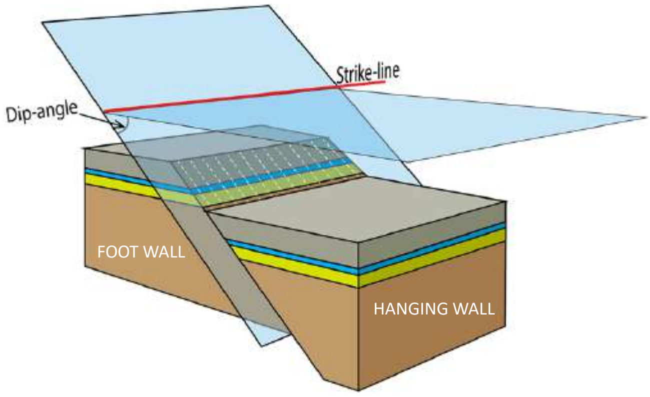
Some typical Mode II structures

Faults

Basics and Definitions

- **Faults** are defined when two adjacent blocks of rock have moved past each other in response to induced stresses. The notion of localized movement leads to two genetically different classes of faults reflecting the two basic responses of rocks to stress: **brittle** and **ductile** (and **Brittle-ductile**).
- **Brittle Faults** are fracture discontinuity along which the rocks on either side have moved past each other in a direction parallel to the fracture plane. A low PT feature.
- **Ductile Faults** (commonly known as **Shear Zones/Ductile Shear Zones**) are narrow zones of localized but continuous ductile displacement between two blocks without developing any fractures at the scale of observation. A high PT feature.

Brittle Faults: Terminologies

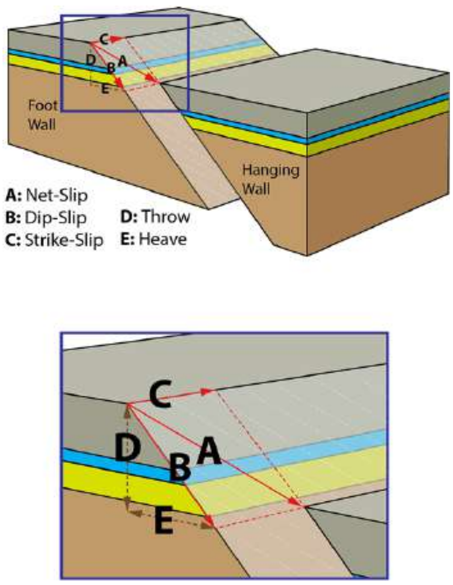


- In outcrop scales, faults generally appear as straight planes. In general, fault surfaces are curved in large scale (seen in 3D seismic data). The fault corrugations thereby identified are attributed to the linkage of fault-segments through time.

- The rock immediately above and below a non-vertical fault or shear zone is referred to as the **hanging wall** and the **foot wall** of the fault, respectively.

- Fault dip > 45° **high angle faults**
  Fault dip < 45° **low angle faults**.

Basic Terminologies of Brittle Faults



- **Net-slip** (**A**) is the direction of movement of the hanging wall relative to the footwall. Its length provides the amount of displacement on the fault, which generally is the addition of several movements.

- The components of the net-slip along dip and strike directions are **Dip-slip** (**B**) and **Strike-slip** (**C**), respectively.

- The offset shown by a planar feature in a vertical cross section perpendicular to the fault is called the **dip separation**. The vertical component of the dip separation is the **throw** (**D**) and the horizontal component (perpendicular to the fault strike) is the **heave**. (**E**).

Note: the dip separation is not equivalent to the dip slip

Basic Classification of Brittle Faults

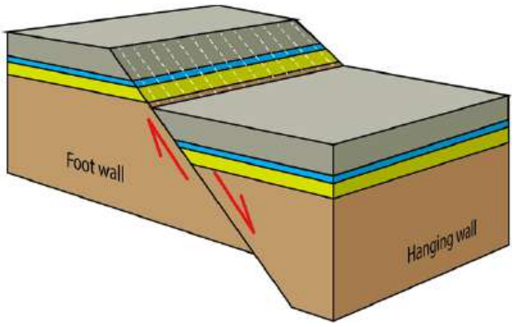
- BRITTLE FAULTS
  - DIP-SLIP FAULTS
    - NORMAL FAULTS
    - REVERSE FAULTS
  - STRIKE-SLIP FAULTS
    - DEXTRAL
    - SINISTRAL
  - OBLIQUE FAULTS

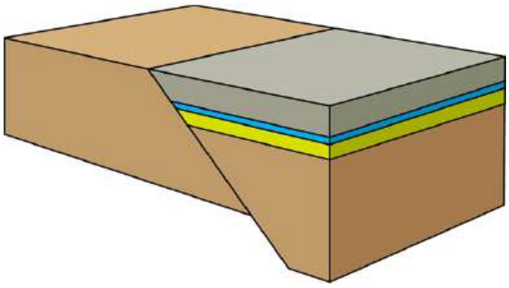
Basic Classification of Brittle Faults

NORMAL FAULT	A **normal fault** is a high angle, dip slip fault on which the hanging-wall has moved down relative to the footwall. A normal fault brings younger rocks over older ones. Because of the separation of geological horizons that results from normal faulting, such faults are also termed **extension faults**.
⇧ DIP SLIP FAULT ⇩	
REVERSE FAULT	A **reverse fault** is a dip slip fault on which the hanging-wall has moved up and over the footwall. Consequently, old rocks are brought over younger ones. A **thrust fault** is a low-angle reverse fault.
STRIKE SLIP FAULT	**Strike slip faults** usually have very steep or vertical dips and the relative movement between the adjacent blocks is horizontal, parallel to the strike of the fault plane. Large strike slip faults are also referred to as **transcurrent faults** and **wrench faults**.
OBLIQUE FAULT	Combination of strike slip fault with normal or reverse fault.

Normal Faults

A **normal fault** is a high angle, dip slip fault on which the hanging-wall has moved down relative to the footwall. A normal fault develops in extensional regimes and brings younger rocks over older ones. Because of the separation of geological horizons that results from normal faulting, such faults are also termed **extension faults**.



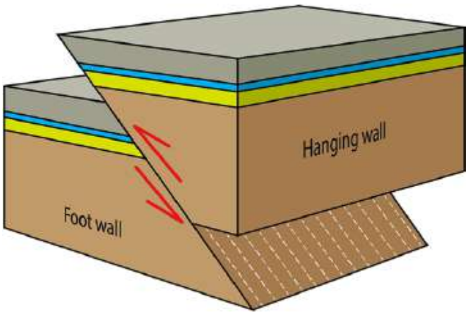


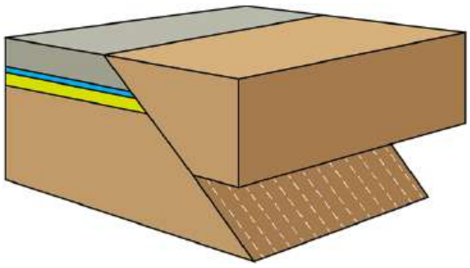
Normal Faults

Normal fault in La Herradura Formation, Morro Solar, Peru. The light layer of rock shows the displacement. A second normal fault is at the right. [Photo: Miguel Vera León]

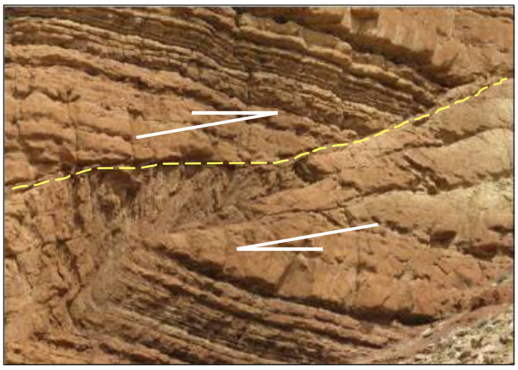
Reverse Faults

A **reverse fault** is a dip slip fault on which the hanging-wall has moved up and over the footwall. Consequently, old rocks are brought over younger ones. A **thrust fault** is a low-angle reverse fault. Reverse faults are produced in compressional regimes.

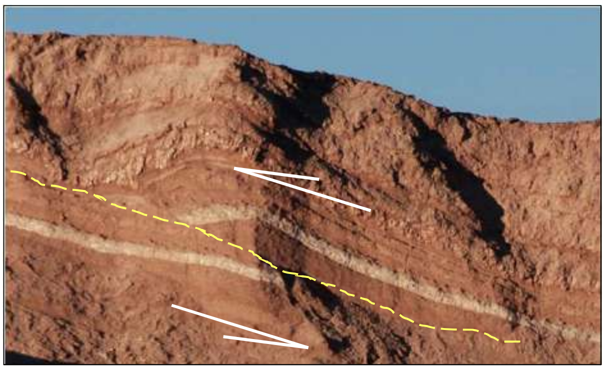




Reverse Faults



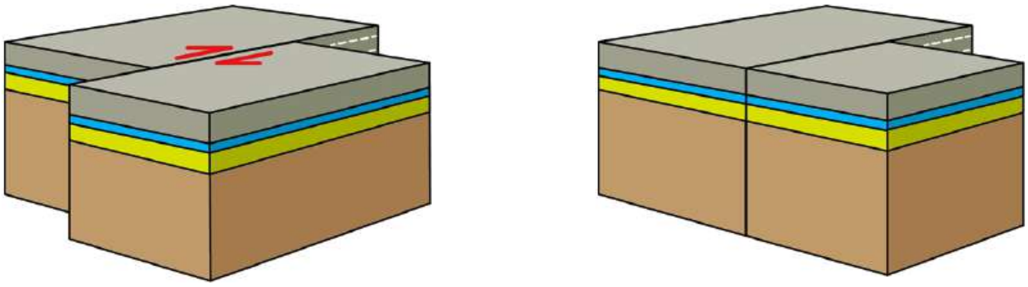
[Photo: Ron Schott, Twitter]



Photograph: Fossen, 2005

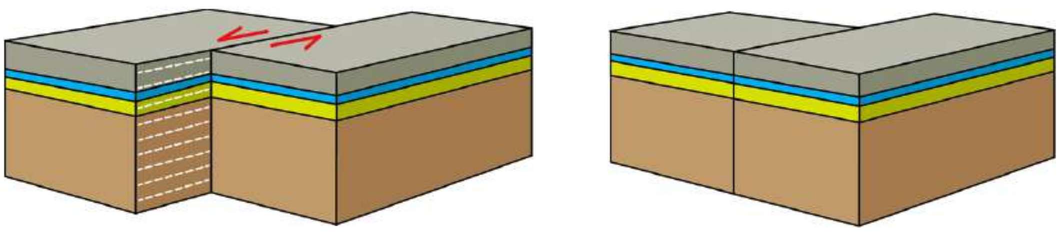
Strike-slip Faults - Dextral

Strike slip faults usually have very steep or vertical dips and the relative movement between the adjacent blocks is horizontal, parallel to the strike of the fault plane.



Strike-slip Faults - Sinistral

Strike slip faults usually have very steep or vertical dips and the relative movement between the adjacent blocks is horizontal, parallel to the strike of the fault plane.

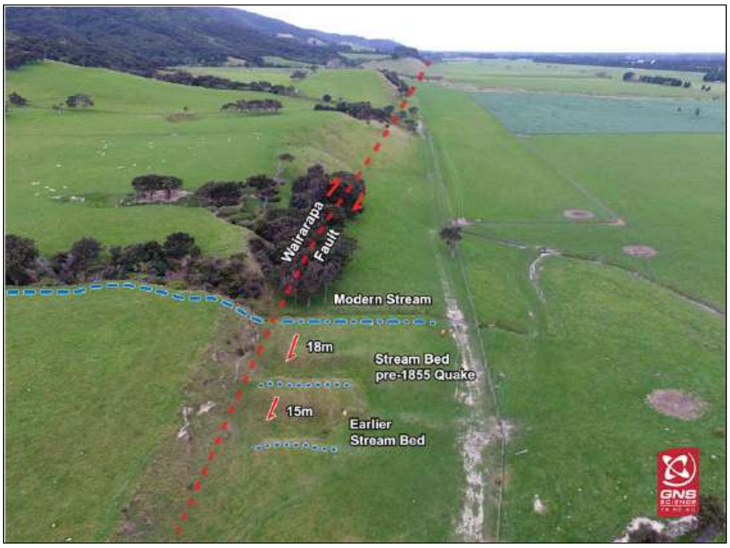


Strike-slip Faults - Sinistral

Small offset from a single earthquake in California (M 6.9 strike-slip event in 1979). [Photograph: Cavit, D, U.S. Geological Survey]

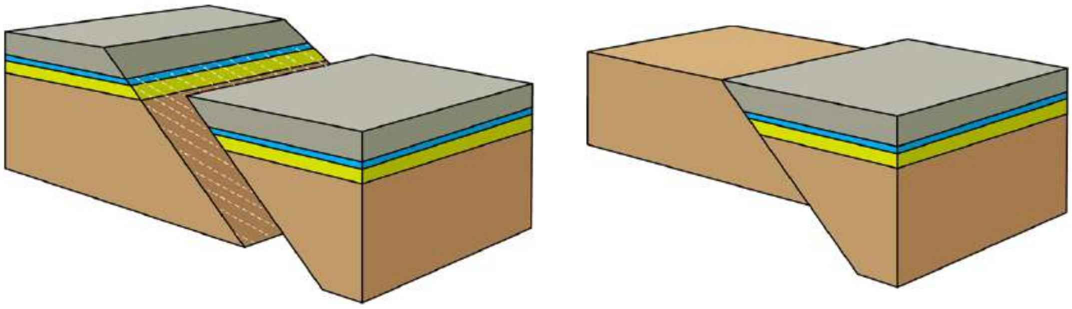
Strike-slip Faults - Dextral

The Wairarapa Fault (near Wellington) is one of New Zealand's large active faults. It was responsible for the massive magnitude 8.2 earthquake that violently shook the lower North Island in 1855 in New Zealand's largest historically recorded 'quake. [Photograph from GNS Science, New Zealand]



Oblique Faults

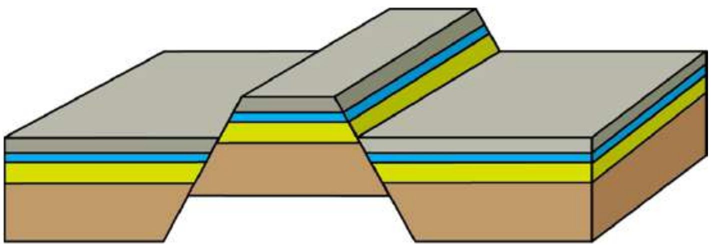
Combination of strike slip fault with normal or reverse fault.



This illustration is with normal-slip components, an oblique fault with reverse slip component is also possible.

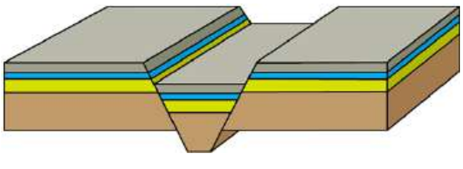
More on Normal Faults

- Normal faults dipping away from each other create an upthrown block called a **horst**.



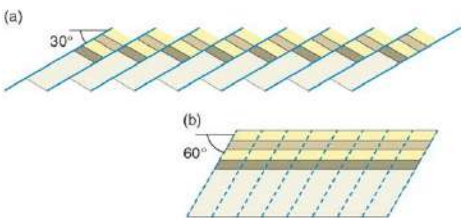
More on Normal Faults

- Normal faults dipping toward each other create a downthrown block known as a **graben**. A one sided graben is known as **half-graben**.



Normal Faults: Domino Model

- Sections through a rifted portion of the upper crust typically show a series of rotated fault blocks arranged more or less like domino bricks or overturned books in a partly filled bookshelf. This analogy has given rise to the name bookshelf tectonics or the (rigid) domino model.



(a) Schematic illustration of rigid domino-style fault blocks. (b) Such fault blocks can be restored by rigid rotation until layering is horizontal. In this case we have applied 30° rotation and displacement removal.

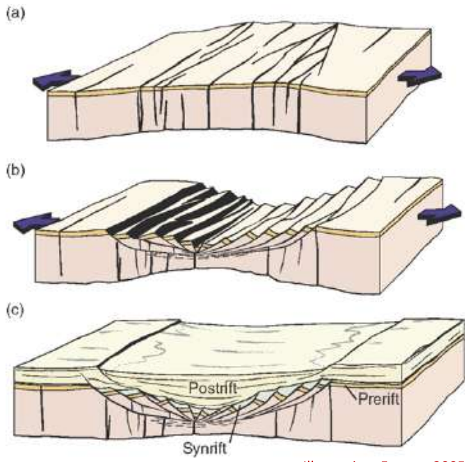


Illustration: Fossen, 2005

Next Lecture

Basic Structures and related terminologies
(Fault, Fold and Shear Zones)

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 22. Folds-and-Foldings

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Definition of a fold in single and multilayer system
- Basic terminologies associated with folds' description

The Concept and Definition

- A fold is represented by a curved surface or a stack of curved surfaces whose initial curvature has increased by deformation.

  - Since stratification in undeformed sedimentary beds is planar within a short distance, a distinctly curved or wavy stratification surface is commonly described as a fold.

  - Folds occur in all scales; from mountain or orogenic belts to sub-microscopic features.

The Concept and Definition

- We mostly observe folds defined by the deformation induced curvatures of sedimentary bedding planes, however, folding is possible and also commonly observed in any layer having competence contrast with associated layers. These include dikes, veins, metamorphic/igneous compositional layers, foliations etc. In general, fold generating layers are commonly termed as "***form surfaces***"

http://maps.unomaha.edu

Photo: Santanu Misra

Photo: Santanu Misra

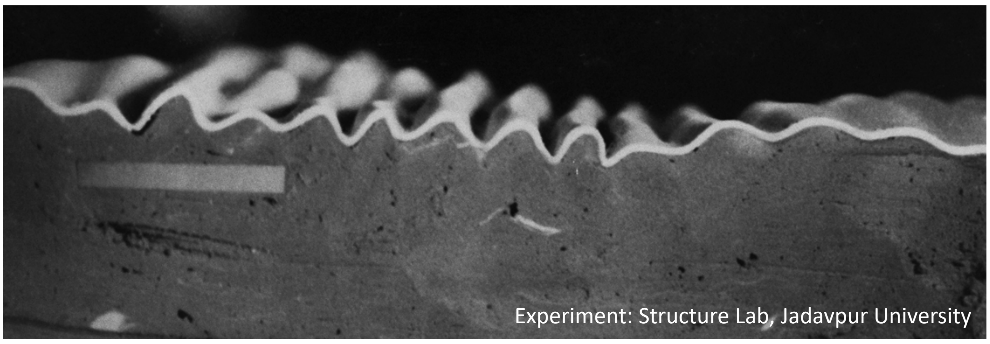
monash.edu.au

Why studding fold in important?

- Fold are one of the most spectacular natural structures.. they are beautiful.
- Fold are studied to reveal their 2D and 3D geometries.
- The shape, orientation and extent of folds are of critical importance in finding economically valuable deposits and predicting their continuity.
- Studying folds and associated structures (foliations, in particular) are also important in revealing the tectonic processes in Earth. The variety of folded structures and shapes record significant information of the many physical, chemical and mechanical aspects of the deformation.

Buckling

- Active folding or buckling is a fold process that can initiate when a layer is shortened parallel to the layering
- A contrast in viscosity is required for buckling to occur, with the folding layer being more competent than the host rock (matrix). The result of buckling is rounded folds, typically parallel and with more or less sinusoidal shape.



Buckling: Characteristics

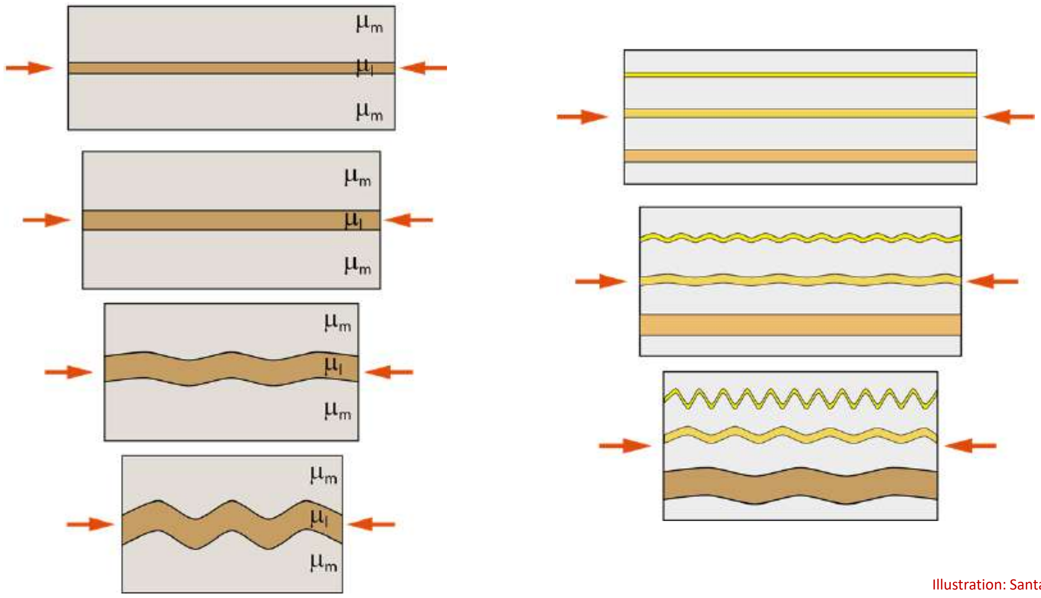


Illustration: Santanu Misra

Bending

Bending occurs when forces act across layers at a high angle, unlike buckle folds where the main force acts parallel to a layer.

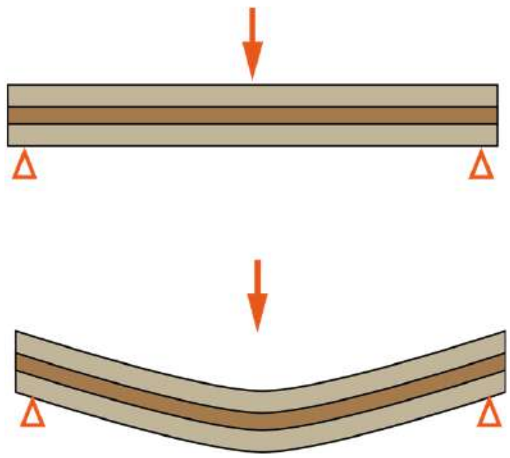


Illustration: Santanu Misra

Passive Folding

Passive folds are produced by accentuation of pre-existing curvatures of layers by more or less homogeneous strain.

The homogeneity of strain is not an essential condition. What is required is that the strain in neighbouring points of the successive layers is approximately the same. This implies that passive folding can take place only if there is no significant competence contrasts among the layers.

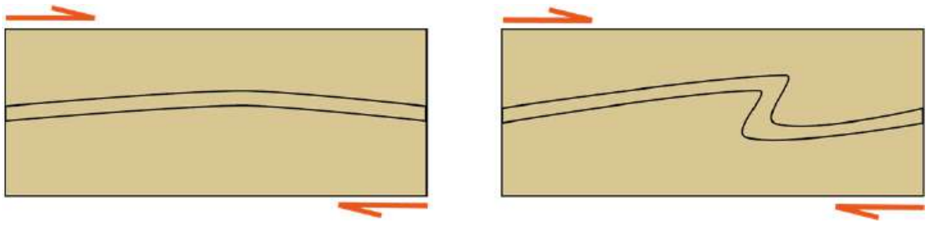


Illustration: Santanu Misra

How to study a folded structure

- The descriptions and associated terminologies of folded structures have evolved through time and they are not always very consistent.
- The defining and constituent elements of the folds can be described best with the characteristic geometries of a single folded surface (an interface between two layers of rocks). A stack of layers can also be folded and termed as multilayer folds.

Photo: Santanu Misra

Photo: Santanu Misra

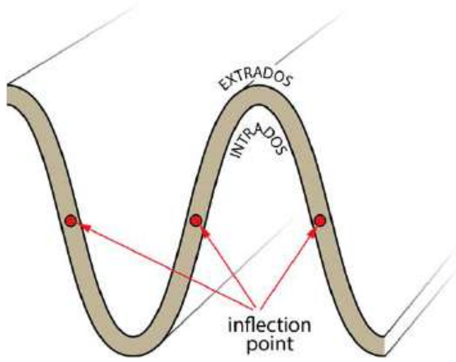
The way we shall learn

- We will first define some special features as points of a single layer fold at its cross section, i.e., where the "waviness" is best visible in 2D.
- We shall extend the points then in the third dimension to understand the linear features of the folds in 3D.
- We finally will connect the lines, wherever possible and applicable to construct some imaginary surfaces, which farther constrain the folded sequence.

Elements of single-layer fold

Inflection point & Fold train

- The trace of a folded surface appears as a wavy line on the plane of the transverse profile.
- A point which separates a convex and a concave segment of the wavy line is called an *inflection point*. In other words, the points of inflection separate, on the transverse profile, fold-segments of opposite senses of curvature.
- The outer- and and inner-arc in fold are *Extrados* are *Intrados*, respectively.
- A *fold train* is a series of folds with alternating senses of curvatures.



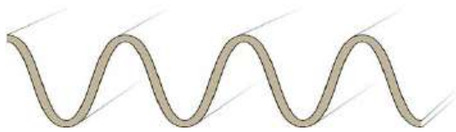


Illustration: Santanu Misra

Elements of single-layer fold

Antiform & Synform

- Fold segments, which are **convex upward**, are *antiforms* and folds that are **concave upward** are *synforms*.
- A fold train is generally characterised by alternate antiforms and synforms.

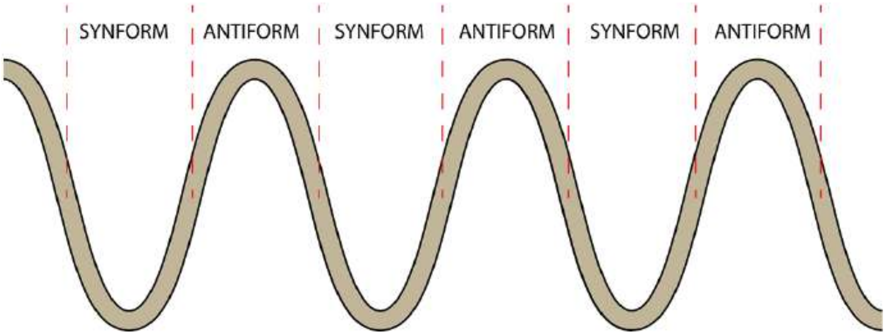


Illustration: Santanu Misra

Sense of Curvature

- **Antiform**: A fold that closes upward
- **Synform**: A fold that closes downward
- **Neutral**: A fold that closes sidewise

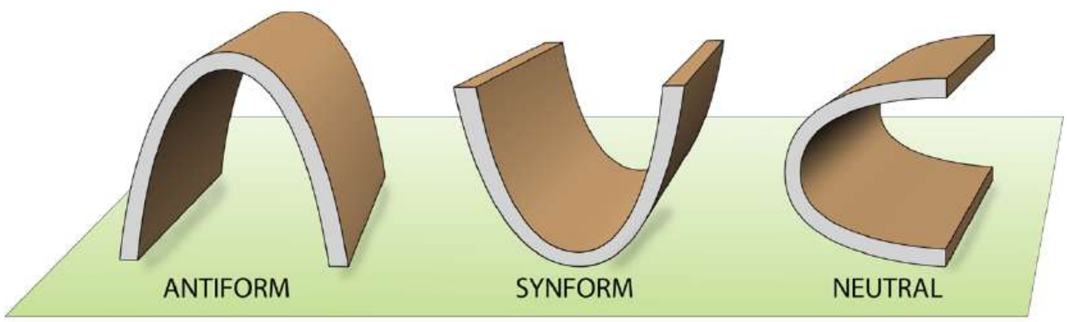


Illustration: Santanu Misra

Stratigraphic Younging Direction to fold closure - I

- **Anticline**: A fold in which the direction of younging is away from the fold core (intrados)
- **Syncline**: A fold in which the direction of younging is towards the the fold core (intrados)

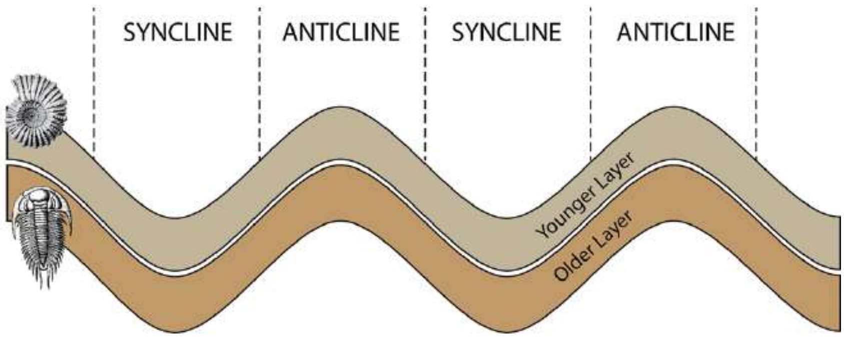


Illustration: Santanu Misra

Stratigraphic Younging Direction to fold closure - III

- **Synformal Anticline**: A fold that closes downward but with direction of younging away from the fold core (intrados)
- **Antiformal Syncline**: A fold that closes upward but in which the younging is towards the fold core (intrados)

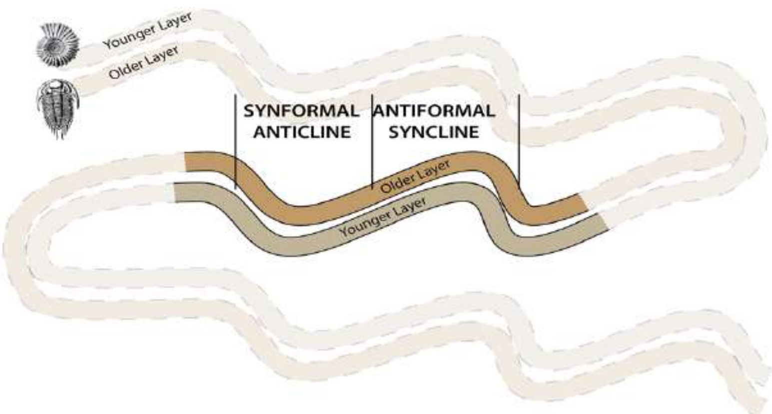


Illustration: Santanu Misra

Symmetry of fold

- **Symmetric Fold**: A fold is symmetric, if in profile, the shape of one side of the hinge is a mirror image on other side and the limbs are identical in length. The plane of symmetry is the axial plane and also the bisector of the median surface.
- **Asymmetric Fold**: A fold that does not have any mirror plane of symmetry, and the limbs are of unequal length.

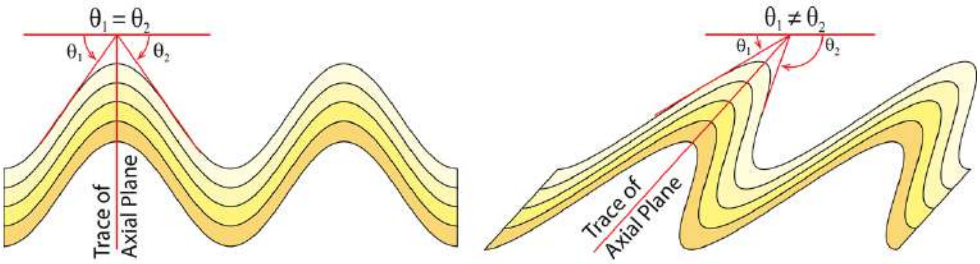


Illustration: Santanu Misra

Elements of single-layer fold

Curvature, Hinge, Limb, Crest and Trough

- Curvature is the measure of the change of orientation per unit distance along the line/surface; a circular arc has constant curvature and straight line has no curvature.
- In a fold train, the curvature is measured from one inflection point to the next.
- In this curved segment, the *hinge* is point where the curvature is largest. A fold segment may have more than one hinge points.
- The *hinge* zone is the segment of highly curved line around the hinge point.
- The *limbs* (*flanks*) are regions of lowest curvatures and includes the inflection points.
- The *crest* and *trough points* are the points of highest and lowest elevations, in a fold train, respectively. Crest and trough, may or may not coincide the hinge points of the fold rain.

Elements of single-layer fold

Curvature, Hinge, Limb, Crest and Trough

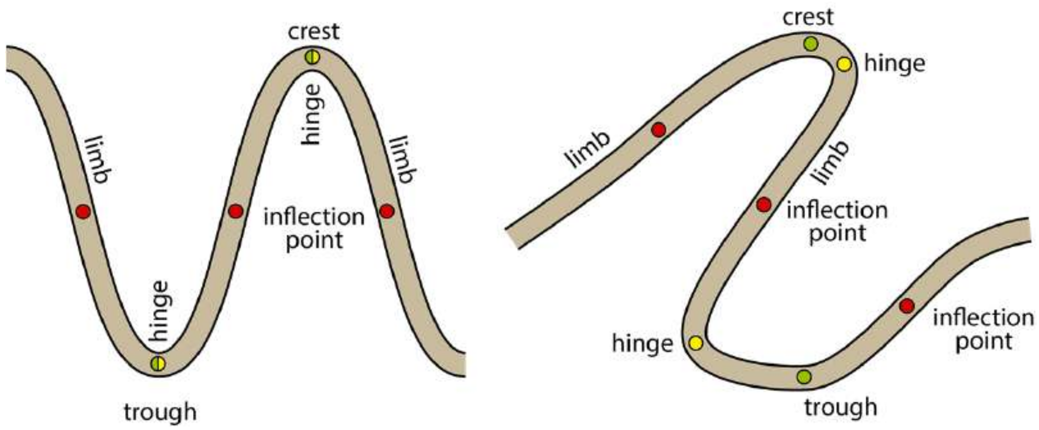


Illustration: Santanu Misra

Elements of single-layer fold

Interlimb angle

Interlimb angle of a folded layer is the angle enclosed by its two limbs.

Interlimb angle measures the tightness of the folded structure.

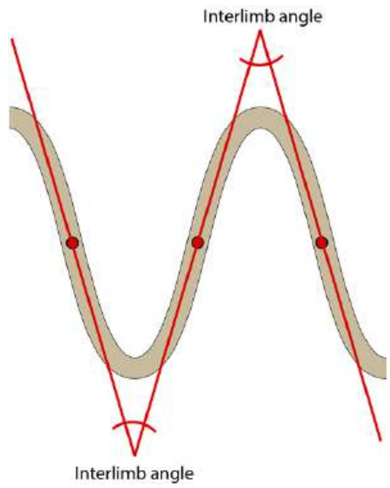


Illustration: Santanu Misra

Elements of single-layer fold

Fold Axis

- A fold axis is a line which, moving parallel to itself, generates the folded surface.

Illustration: Santanu Misra

- The fold axis does not have a fixed position in space; it has only a constant orientation throughout a volume of rock within which the fold is cylindrical.
- The geometry of a cylindrical fold is best described by the orientation of the fold axis along with a description of the section perpendicular to the fold axis. Such a section is called a *transverse profile* or simply a *profile*.

Elements of single-layer fold

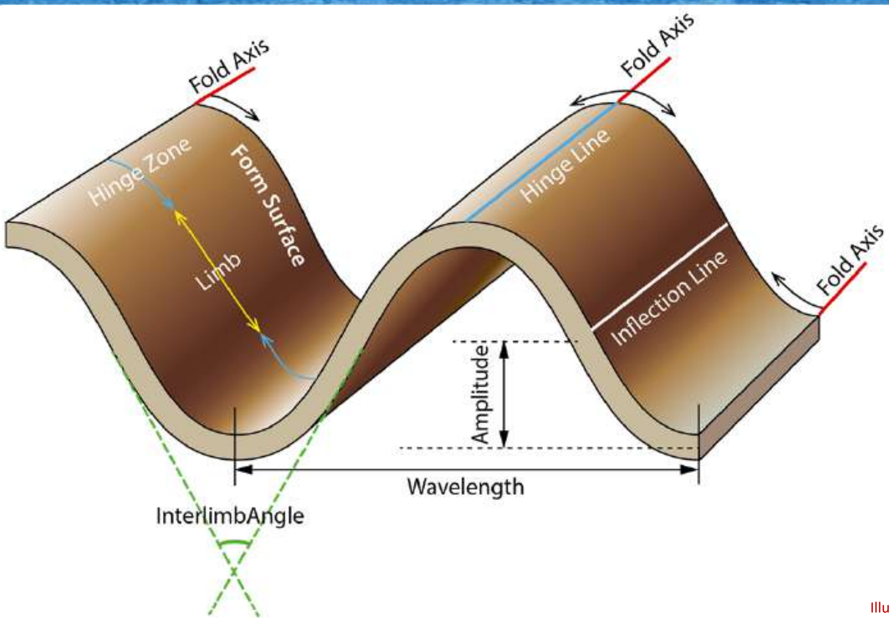


Illustration: Santanu Misra

Elements of single-layer fold

Enveloping Surface, Median Surface, Amplitude and Wavelength

- The *Enveloping Surfaces* are the two surfaces (nor necessarily parallel to each other) that bound the fold train developed in a single folded surface
- The *Median Surface* includes and connects all the inflection lines of a fold train in a single surface.
- The *Amplitude* of any fold is the distance from the median surface to either of the enveloping surfaces measured parallel to the axial surface.
- The *Wavelength* is the distance measured parallel to the median surface, between one point of a fold and the geometrically similar point on a neighbouring fold in the same fold train. For example, the distance from one antiformal hinge to the next antiformal hinge.

Elements of single-layer fold

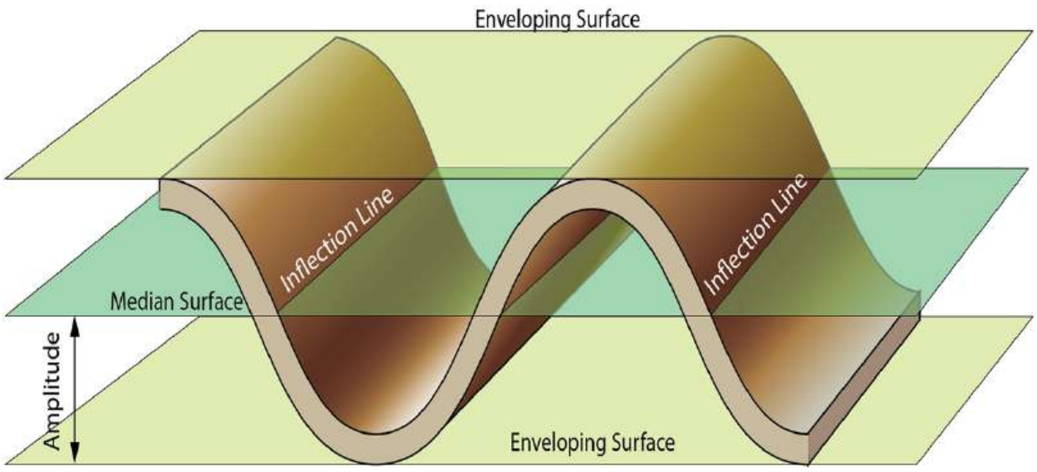


Illustration: Santanu Misra

Elements of single-layer fold

Axial Surface and Trace of Axial Surface

- The surface joining all hinge lines in a particular nested set of folds is generally known as *Axial Surface (Hinge Surface* or *Axial Planes)*.

- The intersection of the axial surface with the form surface (intersection lineation) is known as *Axial Surface Trace* and generally indicate the fold axis of the associated fold.

- The *Axial Surface Trace* can be seen on any other surface (exposure, outcrop, topography) other than the form surface and they are not at all defining the fold axis

Elements of single-layer fold

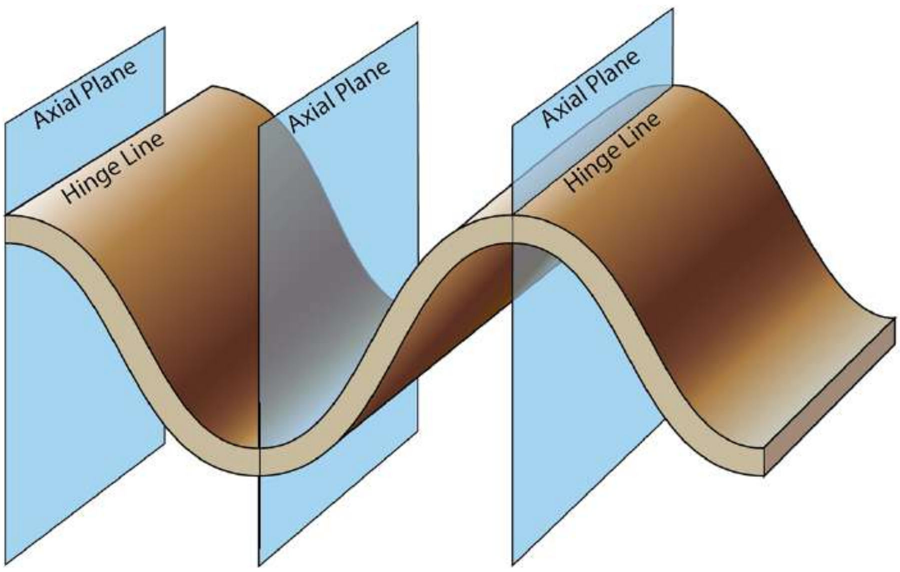


Illustration: Santanu Misra

Elements of single-layer fold

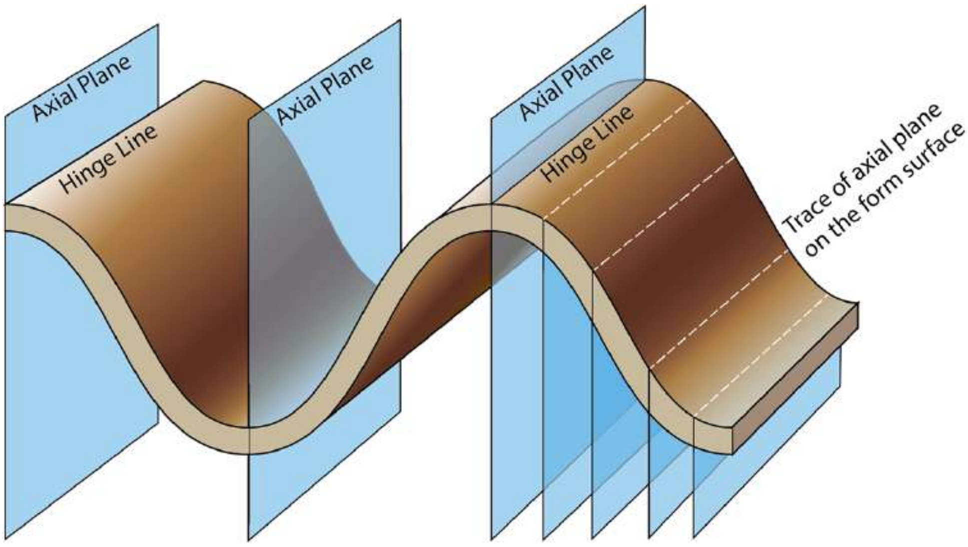


Illustration: Santanu Misra

Fold Interference

Next Lecture

Basic Structures and related terminologies
(Fault, Fold and Shear Zones)

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 23. Ductile Shear Zones

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Definition and characteristics of Ductile Shear Zones
- Foliations in Ductile Shear Zone
- Kinematics of Ductile Shear Zone

Review: Basics and Definitions

Photographs from web and other sources

Review: Basics and Definitions

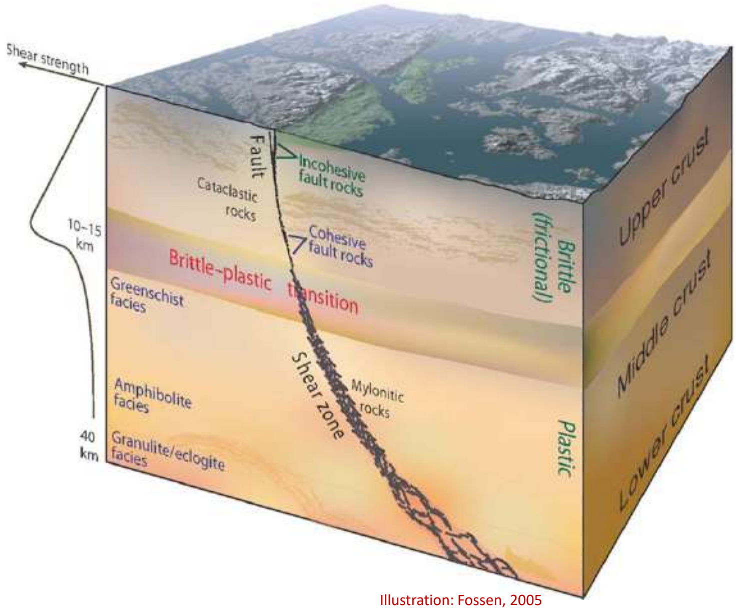


Illustration: Fossen, 2005

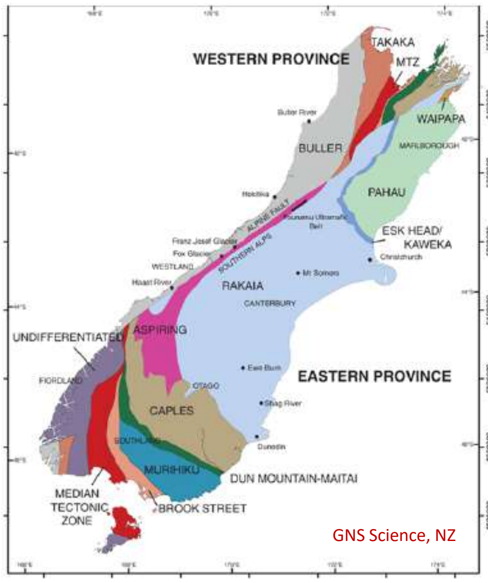
Simplified model of the connection between faults, which normally form in the upper crust, and classic ductile shear zones. The transition is gradual and known as the brittle–ductile transition.

The depth depends on the temperature gradient and the mineralogy of the crust. For granitic rocks it normally occurs in the range of 10–15 km.

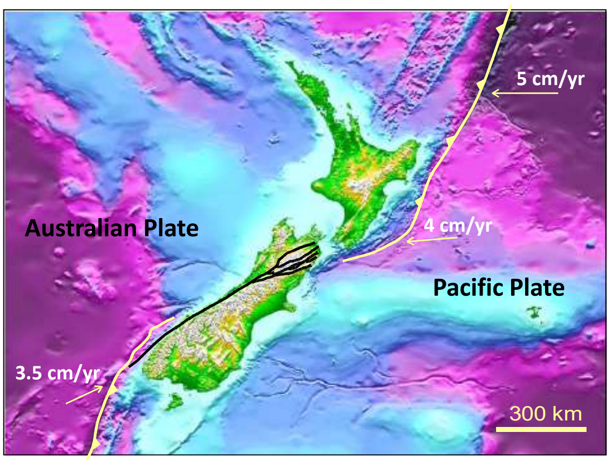
What is a Ductile Shear Zone

- A ductile shear zone is a long narrow zone within which dominantly ductile deformation has caused a localization of large strain compared to the surrounding regions.
- The formation of a ductile shear zone is commonly associated with a drastic reduction of grain size and the development of an extremely foliated (banded) and lineated rock.
- The rock type within a typical ductile shear zone is known as *mylonite* [<u>*mylonite* designates the texture, not the composition of the rock; *breccia* is the rock type within the brittle shear zone</u>]
- Ductile shear zones may range in scale from the microscopic or grain scale to the scale of a few hundreds of kilometres in length and a few millimetres to a few tens of kilometres in width.

A typical Ductile Shear Zone – Large scale



GNS Science, NZ



NIWA, NZ

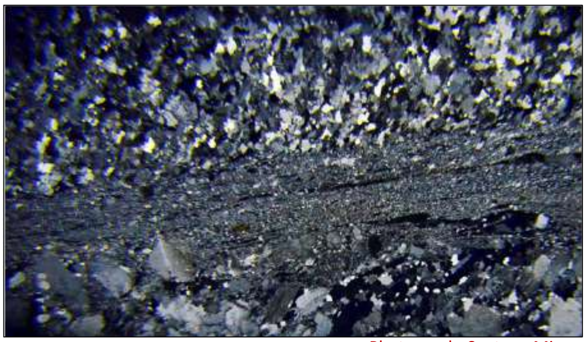
A typical Ductile Shear Zone – Outcrop scale

Photographs: Santanu Misra

Photographs: Santanu Misra

A typical Ductile Shear Zone – Micro scale

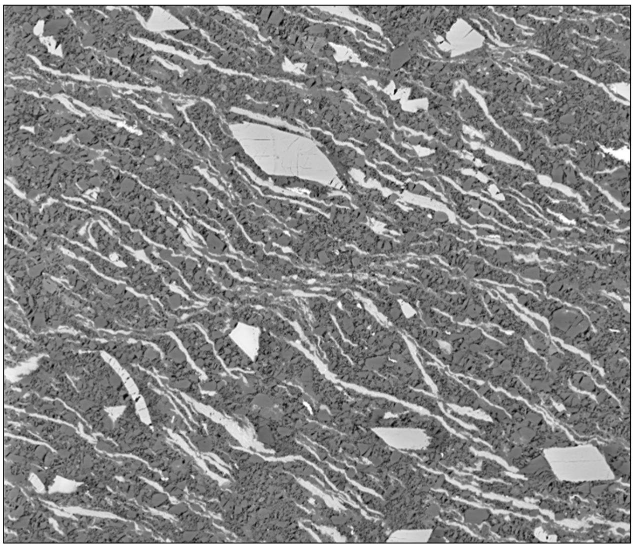
Photograph: Santanu Misra



Photograph: Santanu Misra

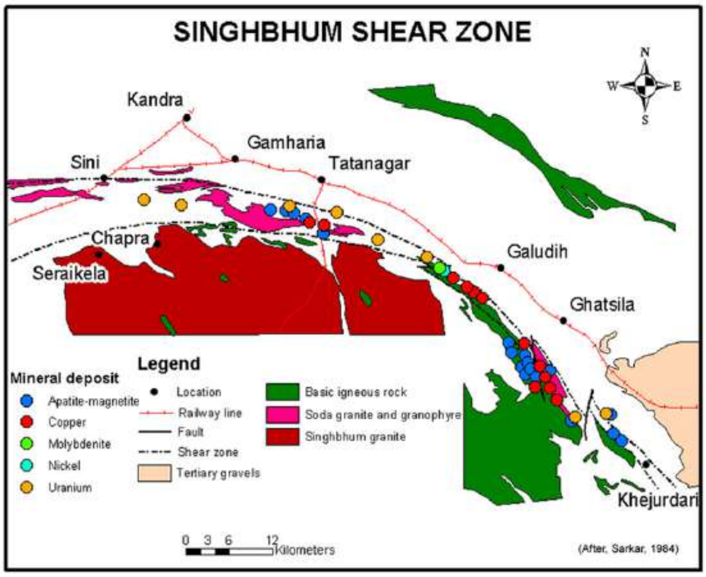
Ductile shear zone in granite. Width of the images 4.2 cm.

A typical Ductile Shear Zone – Micro scale

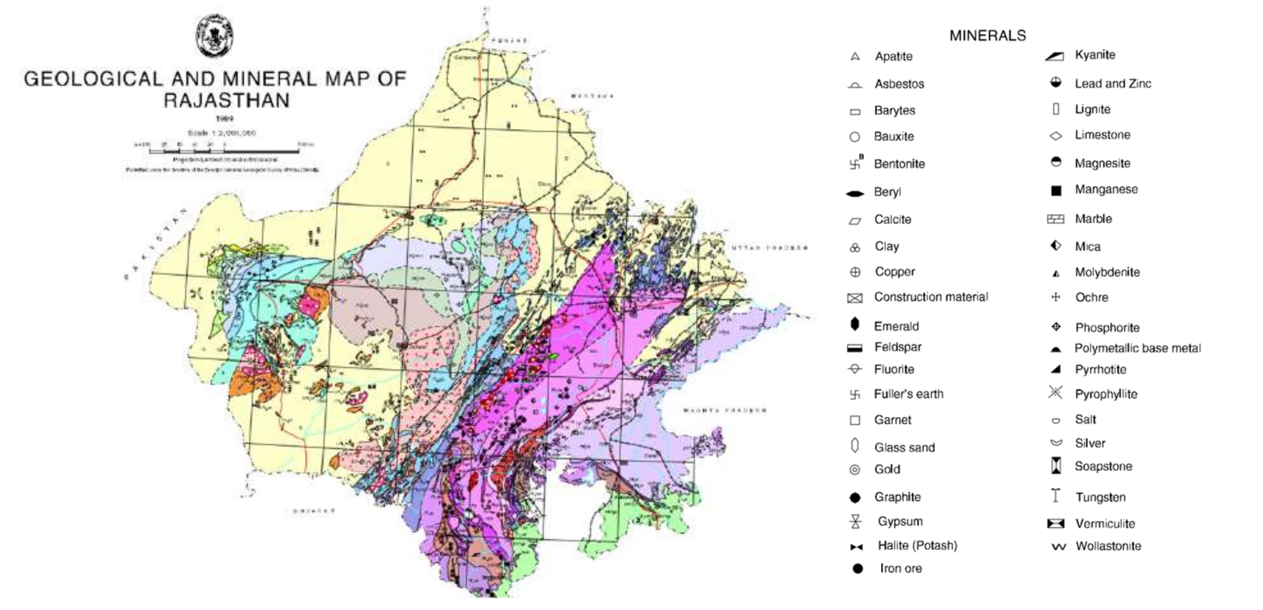


Incipient ductile shear zone in an experimentally deformed quartz (dark)-biotite (bright) aggregate. [Experiment and photo: Santanu Misra; width of the image 400 microns]

Ductile Shear Zone – why so important?



Ductile Shear Zone – why so important?



Ductile Shear Zone – Characteristics

- Strongly foliated (and lineated) rock that has undergone intense ductile deformation (*mylonitization*), with accompanying reduction in grain size.
- Contain fabric elements of monoclinic symmetry.
- Grains, mostly flattened, are much smaller that wall rock.
- Dominantly crystal plastic (intra-crystalline) deformation with/without presence of porphyroclasts.
- Contain planar and linear shape fabric.
- Matured mylonites show two – three *sub-foliations* inclined to each other with certain angles.
- Tight to isoclinal folding, reclined folding, sheath fold.

Shear Zone Rocks

	Random Fabric	Foliated Fabric		Proportion of Matrix	Increasing deformation and decreasing grain size
Non-Cohesive	**Fault breccia** *(visible fragments > 30%)* **Fault gouge** *(visible fragments < 30%)*				
Cohesive	**Crush breccia** *(fragments > 0.5 cm)* **Fine crush breccia** *(fragments 0.1-0.5 cm)* **Crush micro-breccia** *(fragments < 0.1 cm)*		0-10%		
	Protocataclasite	Protomylonite	15-20%		
	Cataclasite	Mylonite	50-90%		
	Ultracataclasite	Ultramylonite	90-100%		
	BRITTLE	**DUCTILE**			

Mylonite

Protomylonite

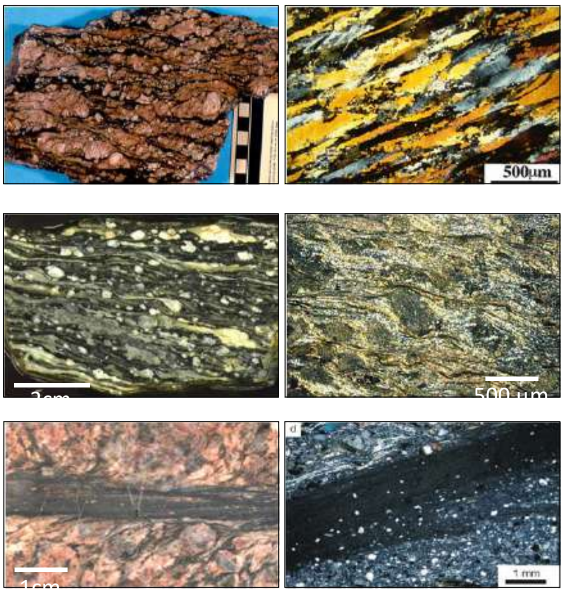
- Grain size > 50 µm
- Percentage matrix < 50%
- Small recrystallized grains surround large relict grains (mortar texture).

Mylonite (Orthomylonite)

- Grain size < 50 µm
- Percentage matrix 50%-90%
- Strongly foliated with porphyroclasts in fine-grained matrix

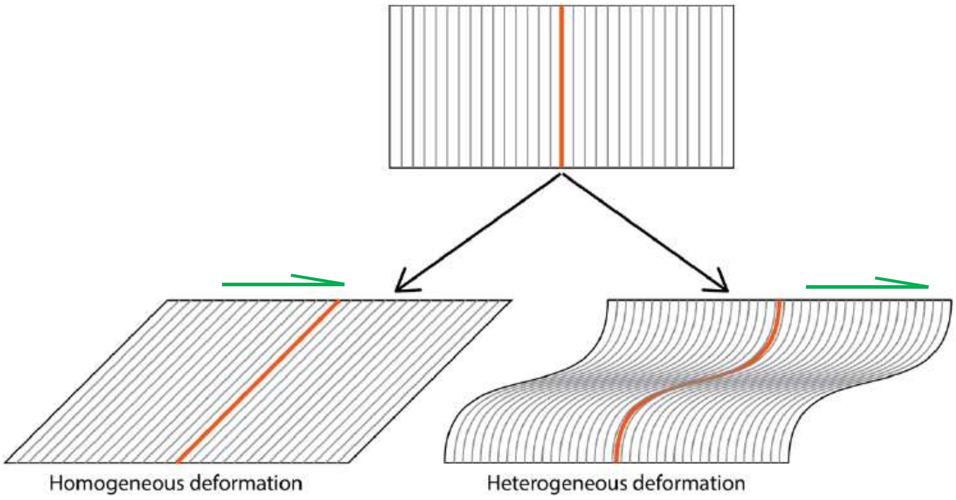
Ultramylonite

- Grain size < 10 µm
- Percentage matrix > 90%
- Thoroughly deformed fine-grained rock

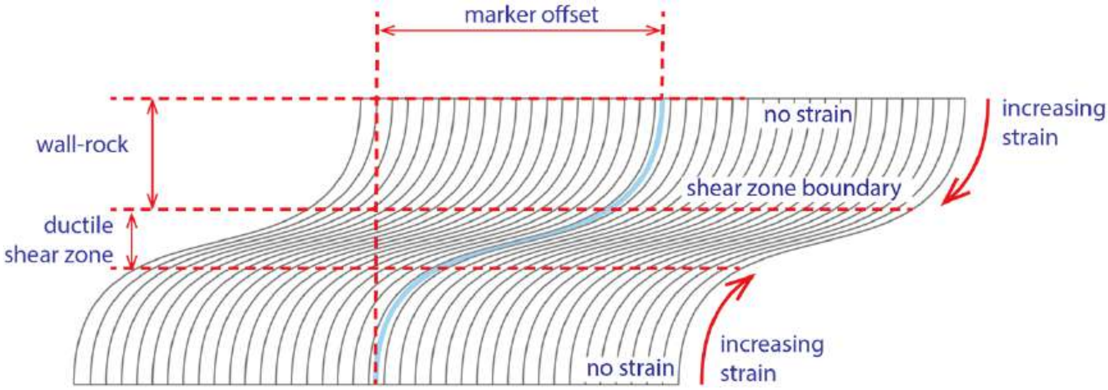


Photographs from various sources and self

Anatomy of a Ductile Shear Zone



Anatomy of a Ductile Shear Zone

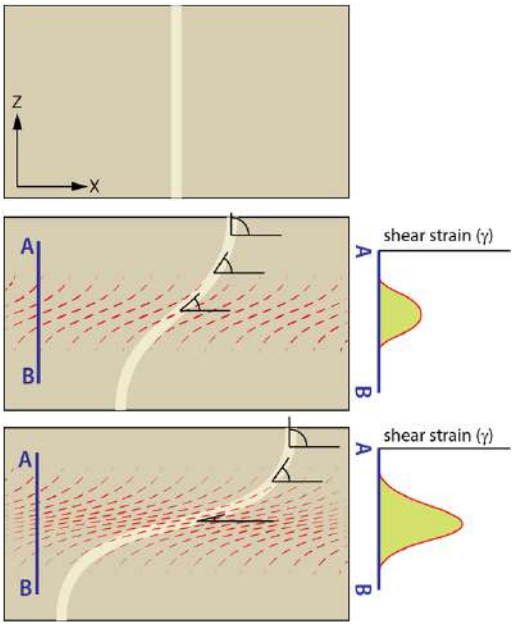


Foliations in Ductile Shear Zone

Shear zones are with genetically related foliation. The foliation makes 45° with the shear zone along the margins. This angle is reduced as strain increases toward the center of the zone.

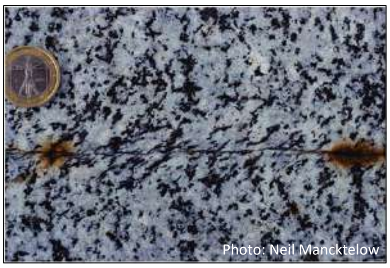
The displacement (d) can be found either by measuring or calculating the area under a shear strain profile across the zone if the deformation is simple shear.

$$d = \int_A^B \gamma dy$$



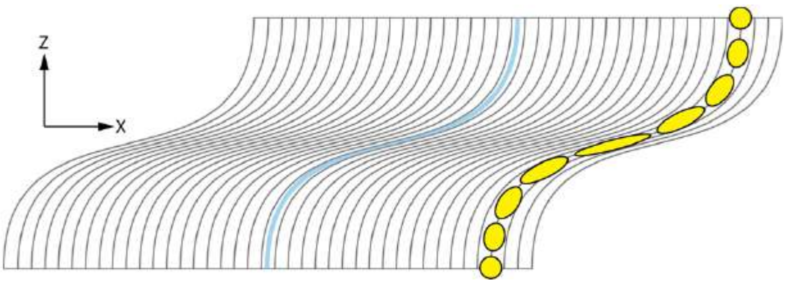
Foliations in Ductile Shear Zone

- A typical shear zone is characterized by development of foliation (tracks the XY plane of the strain ellipsoid), orientation of which depends on geometry, nature and strain of the shar zone.
- In a fairly isotropic rock, a faint foliation will appear at low shear strains but intensity increases with larger shear strain.



Foliations in Ductile Shear Zone

Kinematics of a Ductile Shear Zone



Kinematics of a Ductile Shear Zone

In the strongly deformed domains, the stretching lineation can be equated with the shear direction. The curved or **sigmoidal pattern of the foliation** in the XZ sections of rocks defines the **sense of shear**. The bulk acute angle of the foliation to the shear zone walls is always sympathetic to the sense of shear.

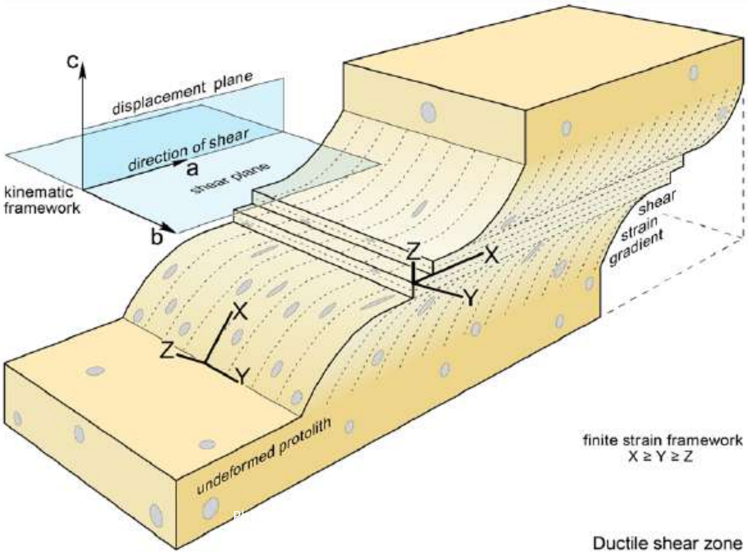


Illustration: Jean Pierre Burg

Kinematics of a Ductile Shear Zone

- Most the mylonites contain structures that show monoclinic (low) symmetry, simply referred to as *asymmetric structures*. The asymmetry is related to the rotational component or non-coaxiality of the deformation, or the fact that objects rotate in a preferred direction.
- The (a)symmetry of mylonite structures can be used to evaluate the sense of shear and sometimes also the degree of coaxiality of a mylonite zone

Where to see?

- ***XZ section of the strain ellipsoid***
- ***Perpendicular to foliation, parallel to lineation.***

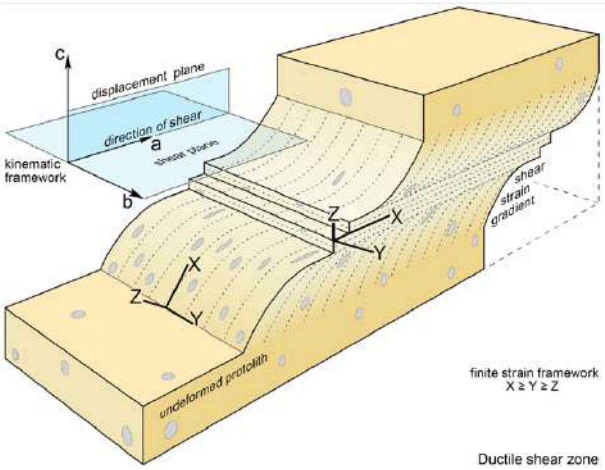


Illustration: Jean Pierre Burg

Some Typical Shear Zone Structures (on XZ plane)

- Foliation Drag; deflected markers
- Internal foliations (C, S and C')
- Mica Fish
- Delta (δ), sigma (σ) and Phi (ϕ) structures
- Sigmoidal veins
- Sheath Folds
- Fractured minerals
- Asymmetric Folds

Know more here:
https://youtu.be/EX8oH48hglw?list=PLHyuArGIlyyR_2mObwQ3yng18LDnDqidp

Next Lecture

ALL THE BEST FOR THE
MID-SEMESTER EXAMINATION

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 24. History of the Earth

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Methods of Studying the Past
- Reconstruction of history from stratigraphic records

Reading:
Marshak's Book (Part-IV)
Grotinger & Jordan's book (Chapter 8)
[*for the entire week*]

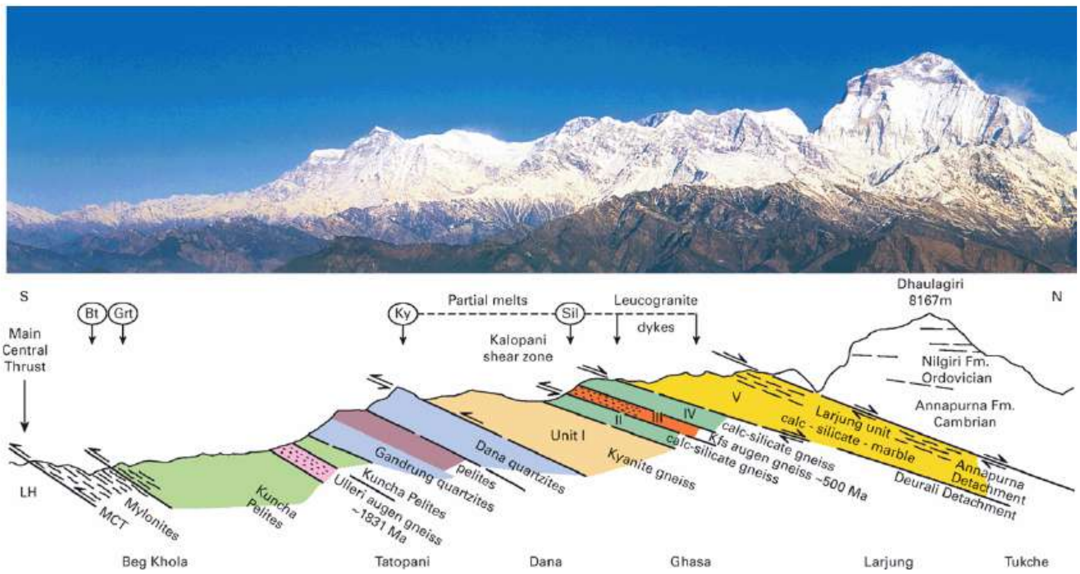
Earth has a History

- Geologic materials record enormous changes.
- Earth is a complex, evolving system.

- Physical and biological systems continuously interact.

- Earth constantly changes and has done so through time.
  - Species arise, flourish, and disappear forever.
  - Continents rift, drift, and collide.
  - Ocean basins open and close.
  - Sea level rises and falls.

Earth has a History



Searle, 2017

Methods of studying the past

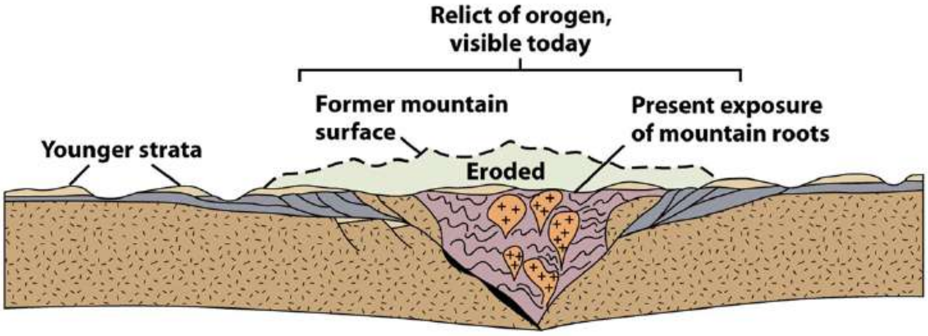
- Historic Earth changes are measured by…
  - Orogenic events.
  - Sea level.
  - Climates.
  - Living organisms.
  - Continental positions.
  - Plate boundaries.
  - Chemistry.
    - Atmosphere.
    - Ocean.
  - Depositional environments.
- These changes are recorded in rocks.

Challenges:
- Discontinuous record
- Erosion
- Younger rocks are better preserved; older rocks less

- **There are still abundance of evidences**

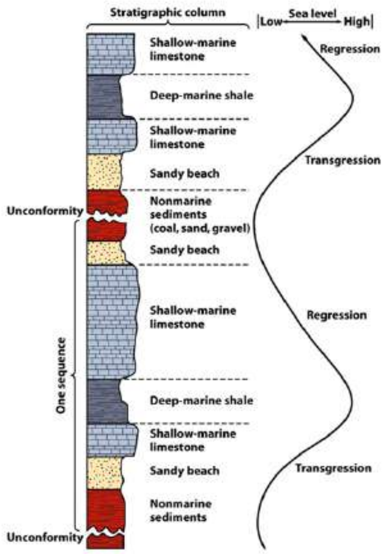
Ancient Orogens

- Ancient orogens – Former mountain belts.
  - Igneous activity, deformation, and metamorphism.
  - Thick sedimentary deposits filling foreland basins.
  - Ancient orogenic belts expose deeply buried rocks.

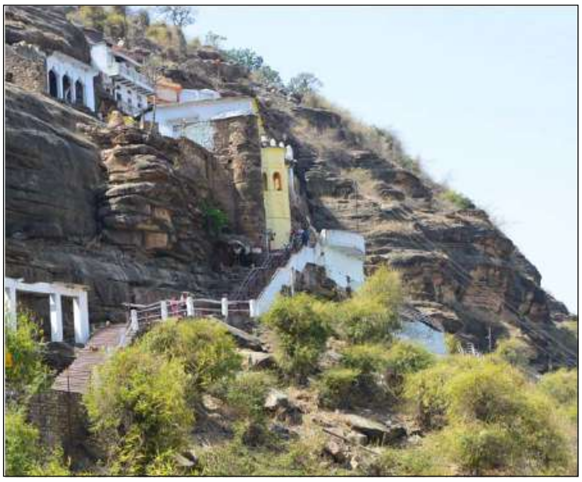


Depositional Environments

- Recognizing depositional environments.
  - Successions of strata record changes in depositional settings.
- Recognizing sea level changes.
  - Sediments record sea level flux.
  - Shallow and deep environments create distinctive sediments.

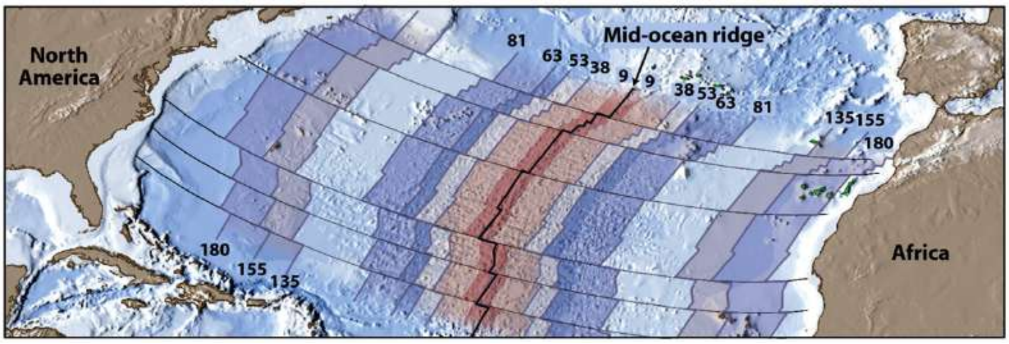


Depositional Environments



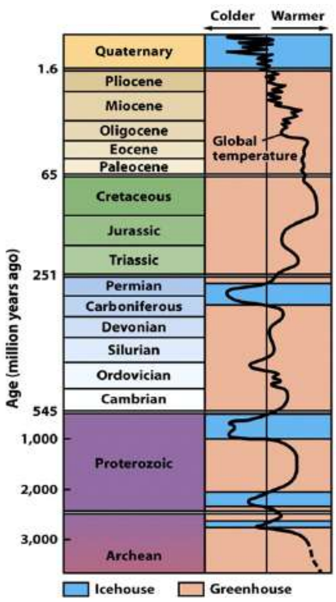
Changing Continental Positions

- Changing continental positions are preserved.
  - Paleomagnetism captures paleolatitude.
  - Ocean width changes by reversing sea-floor anomalies.
  - Rock and fossil distributions compare across oceans.



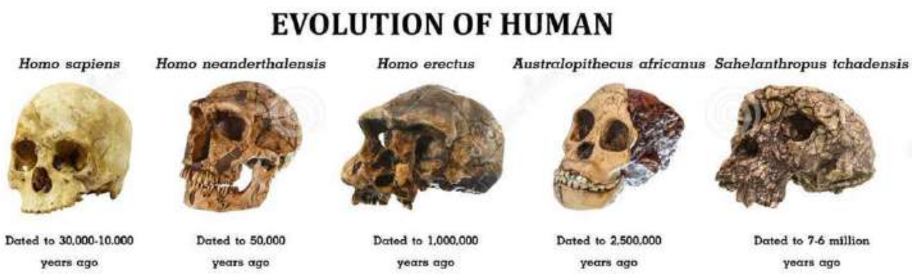
Palaeoclimate

- Paleoclimates – Rocks preserve ancient climates.
  - Tropical – Extensive coral reefs.
  - Subtropical – Extensive deserts.
  - Polar – Extensive glacial deposits.
- Climatic belts expand and contract.
  - Greenhouse Earth.
  - Snowball Earth.
- $^{18}O/^{16}O$ isotopic ratios preserve ancient temperatures



Evolution of Life

- Evolution – Fossils preserve changes in Earth's life.
  - Sedimentary rocks preserve fossil ecosystems.
  - Organisms inhabiting Earth have obviously changed.
    - Over geologic time, most species have exhibited both…
      - Trends toward specialization.
      - Catastrophic extinctions.



Evolution of Life

Archaeopteryx fossil

20,000-Year-Old Human Footprints

History from Stratigraphic Records

Stratigraphy is a branch of geology concerned with the study of rock layers (strata) and layering (stratification). It is primarily used in the study of sedimentary and layered volcanic rocks.

Original horizontality: all rock layers were originally horizontal (*Nicolaus Steno*).

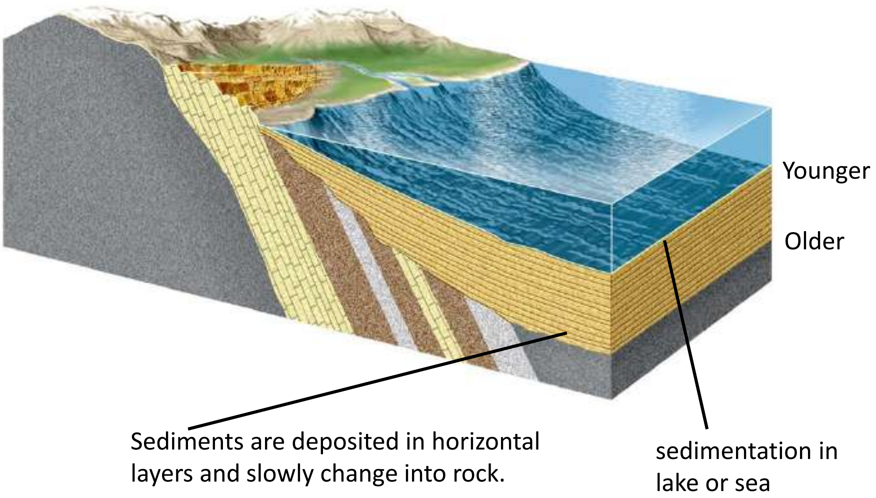
Superposition: in a sequence of sedimentary rock layers, each layer of rock is older than the layer above it and younger than the rock layer below it (*Nicolaus Steno*).

Faunal succession: fossils occur in a definite, invariable sequence in the geologic record (*William Smith*).

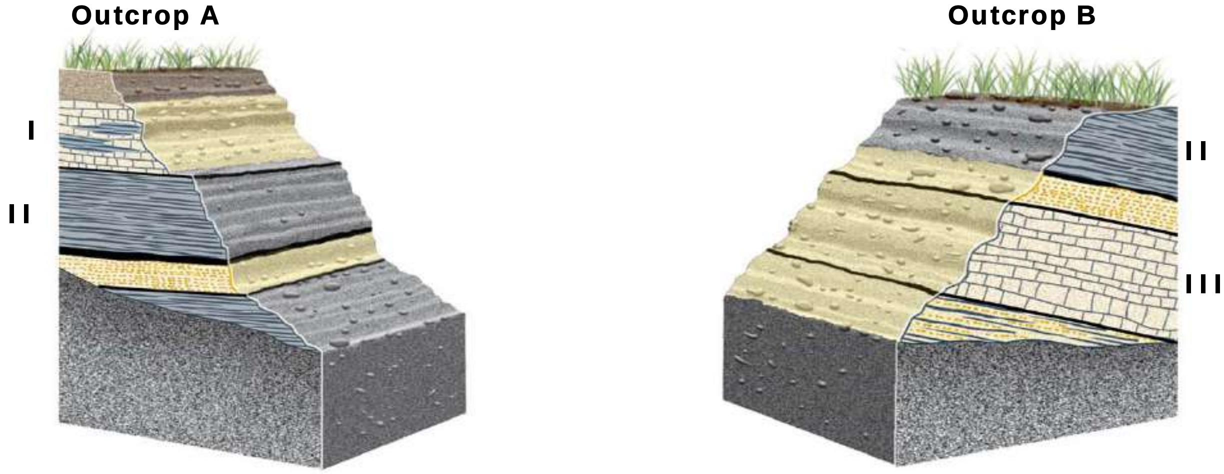
Cross-cutting relationship: if a fault or other body of rock cuts through another body of rock then it must be younger in age than the rock through which it cuts and displaces (*James Hutton*).

Laws of inclusions: if a rock body contained fragments of another rock body, it must be younger than the fragments of rock it contained. The intruding rock must have been there first to provide the fragments. (*James Hutton*).

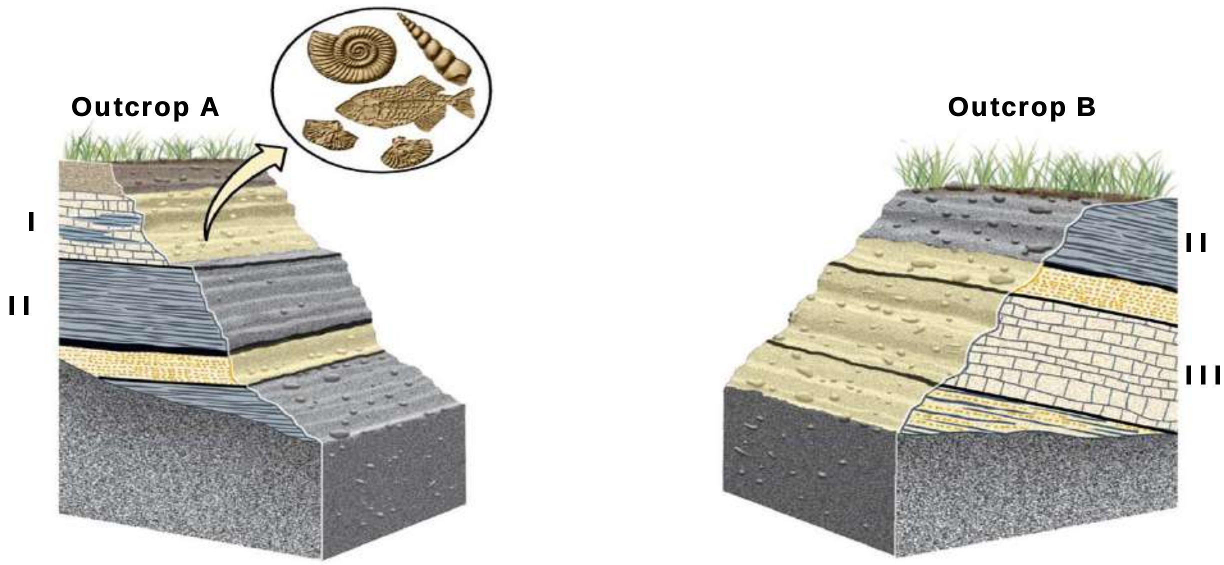
Original Horizontality and Superposition



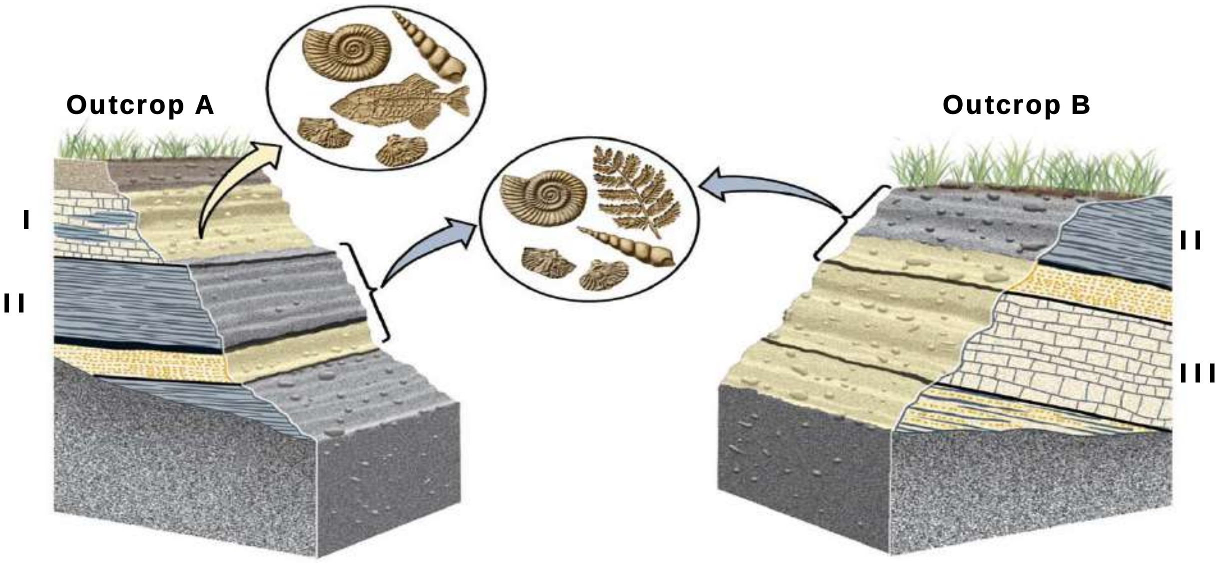
Faunal Succession



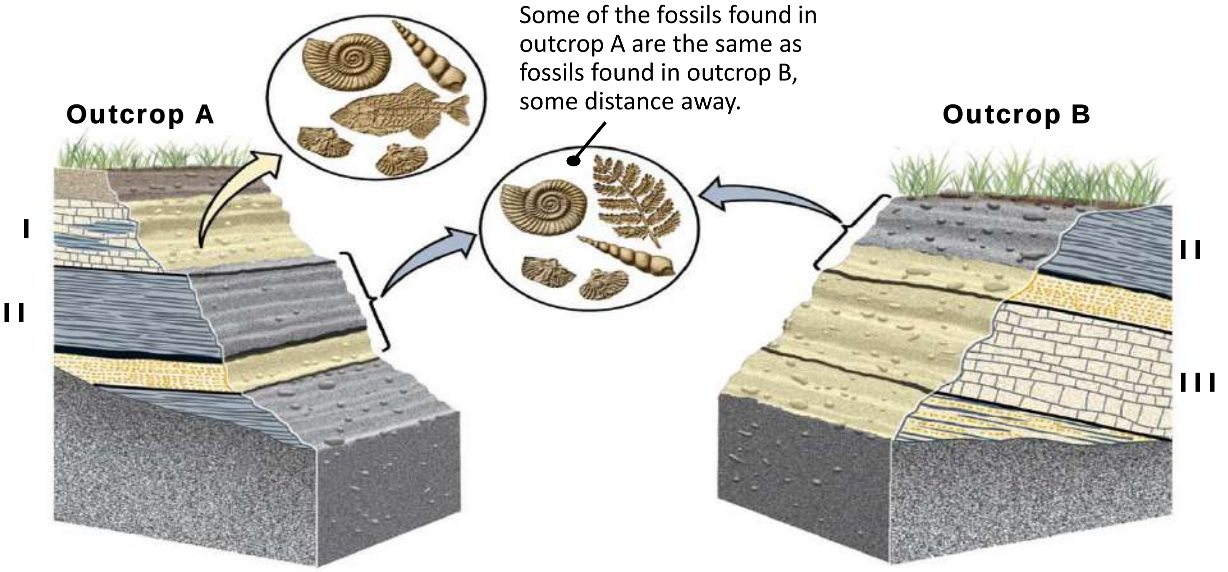
Faunal Succession



Faunal Succession

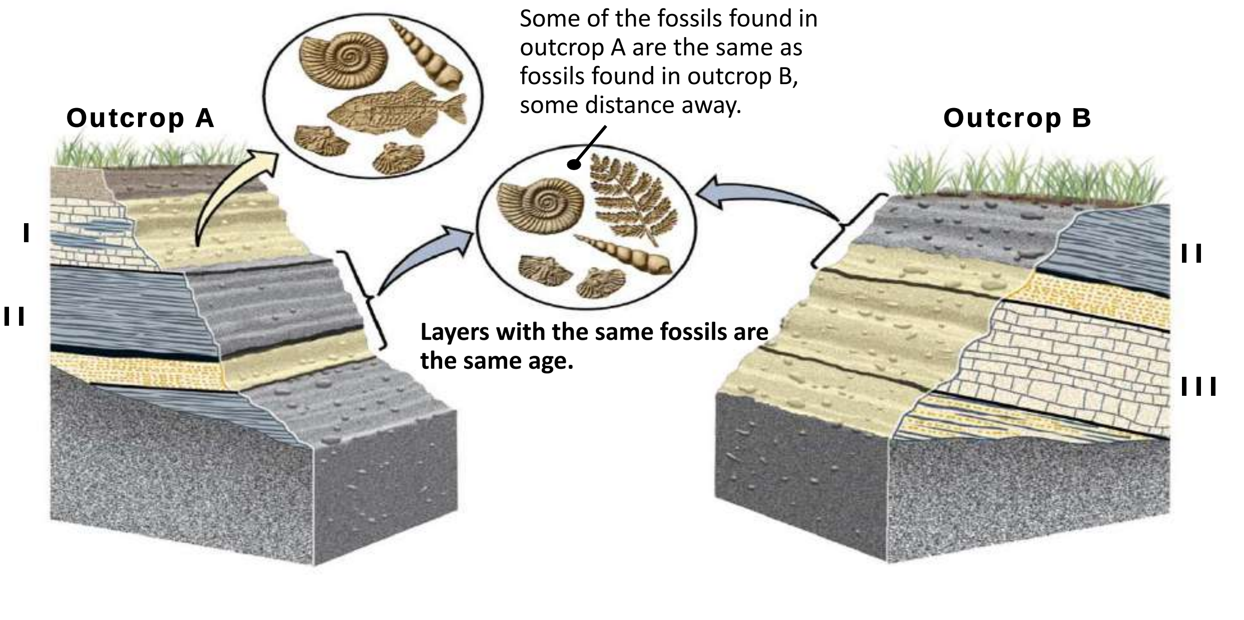


Faunal Succession

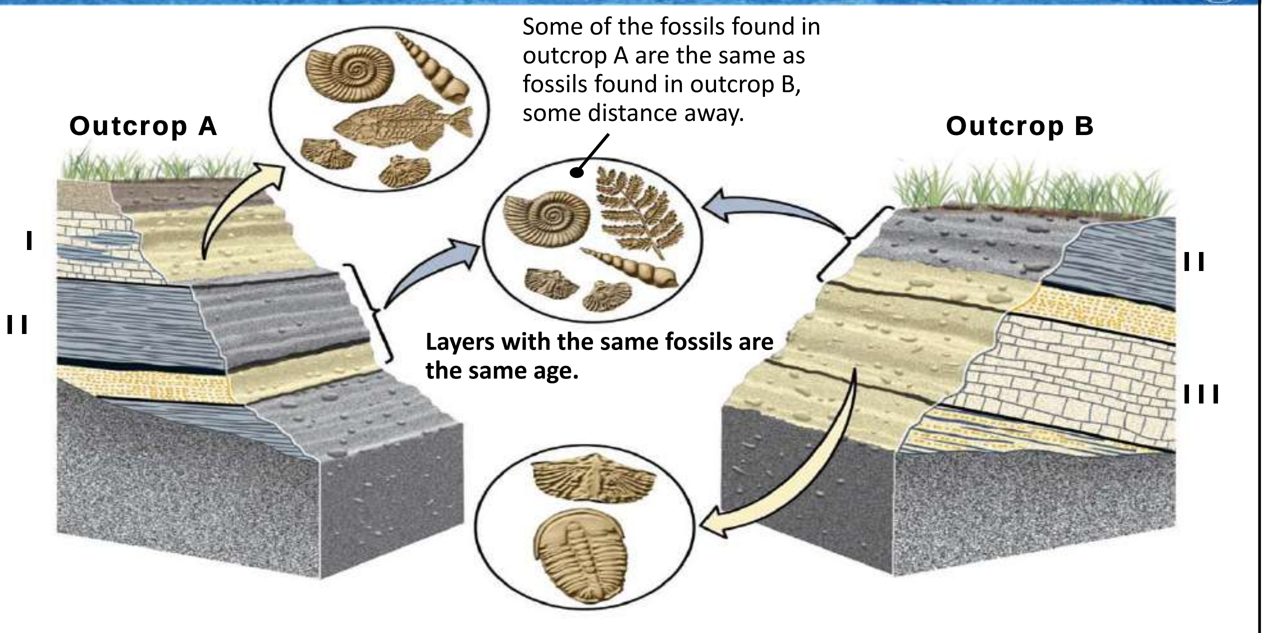


Some of the fossils found in outcrop A are the same as fossils found in outcrop B, some distance away.

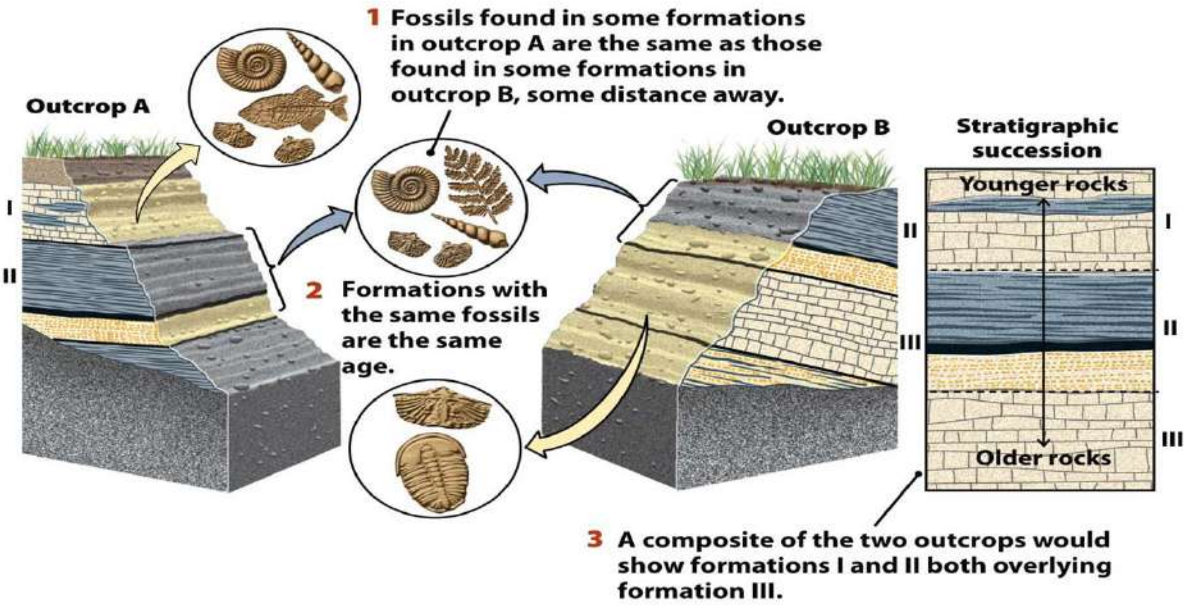
Faunal Succession



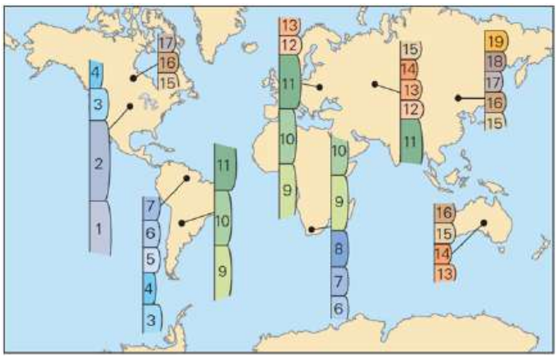
Faunal Succession



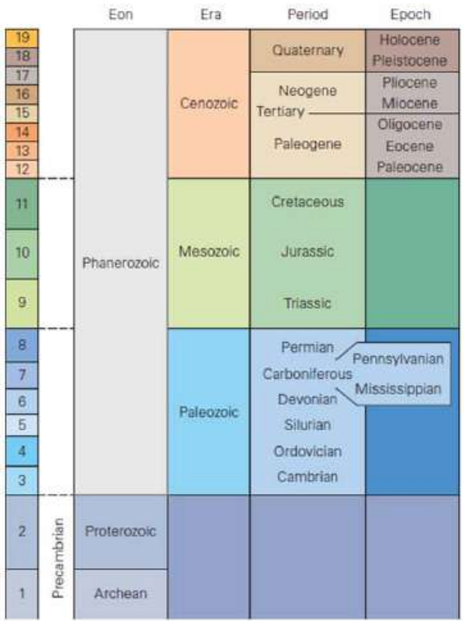
Faunal Succession



Faunal & Stratigraphic Succession



By correlation, the strata from localities around the world can be stacked in a chart representing geologic time to create the geologic column. Geologists assigned names to time intervals, but since the column was built without knowledge of numerical ages, it does not depict the duration of these intervals.



Stratigraphic Records

- Unconformities – gaps in the record

Disconformity: an unconformity between parallel layers of sedimentary rocks which represents a period of erosion or non-deposition. Disconformities are marked by features of subaerial erosion. This type of erosion can leave channels and paleosols in the rock record

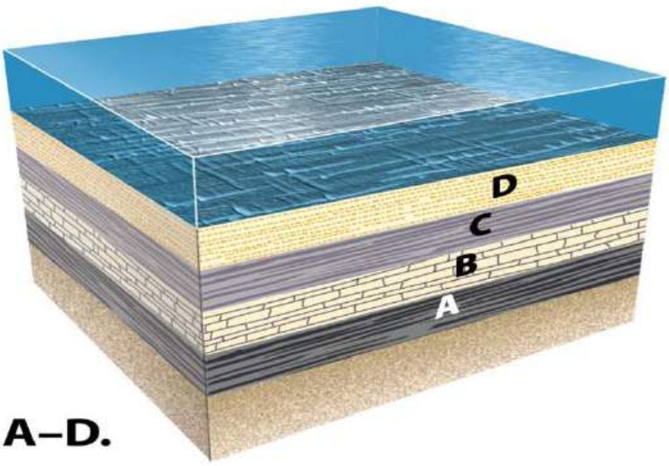
Nonconformity: A nonconformity exists between sedimentary rocks and metamorphic or igneous rocks when the sedimentary rock lies above and was deposited on the pre-existing and eroded metamorphic or igneous rock.

Angular Unconformity: an unconformity where horizontally parallel strata of sedimentary rock are deposited on tilted and eroded layers, producing an angular discordance with the overlying horizontal layers.

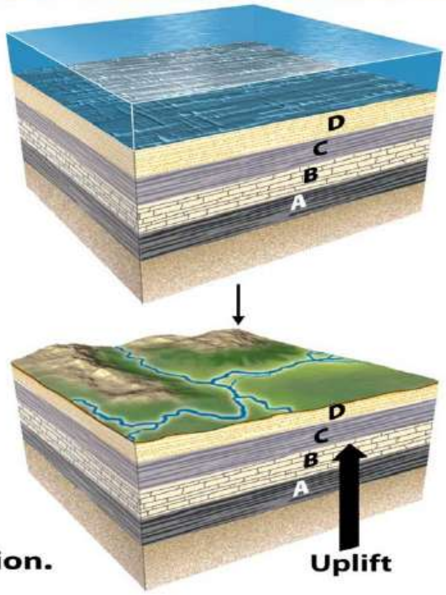
Paraconformity: a type of unconformity in which strata are parallel; there is no apparent erosion and the unconformity surface resembles a simple bedding plane. It is also called nondepositional unconformity or pseudoconformity. A paraconformity of shorter time period is known as Diastem.

Disconformity

TIME 1
Beneath the ocean, sedimentary beds accumulate in layers A–D.

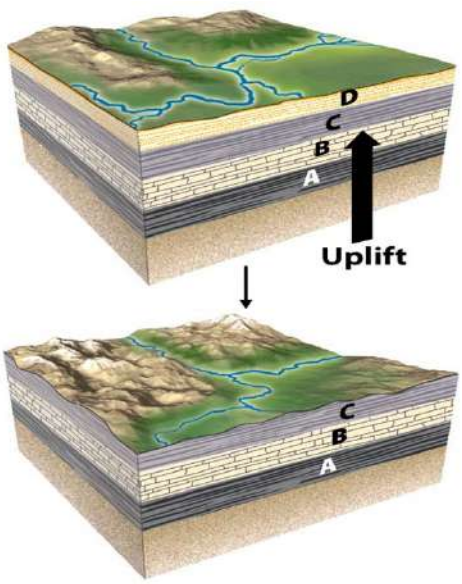


Disconformity



TIME 2
Later, tectonic forces cause uplift of the beds above sea level, exposing them to erosion.

Disconformity

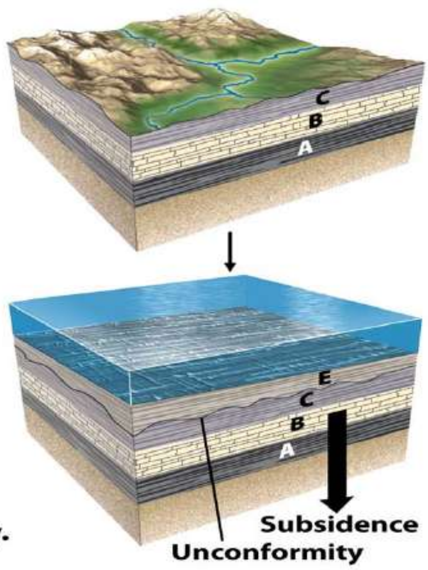


TIME 3
Erosion strips away layer D and part of C, leaving an irregular surface of hills and valleys.

Disconformity

TIME 3
Erosion strips away layer D and part of C, leaving an irregular surface of hills and valleys.

TIME 4
Subsidence below sea level allows a new layer, E, to be deposited over C. The irregular surface of C is preserved as an unconformity.



Disconformity

TIME 1
Beneath the ocean, sedimentary beds accumulate in layers A–D.

TIME 2
Later, tectonic forces cause uplift of the beds above sea level, exposing them to erosion.

TIME 3
Erosion strips away layer D and part of C, leaving an irregular surface of hills and valleys.

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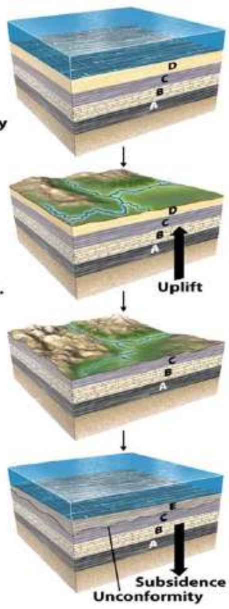
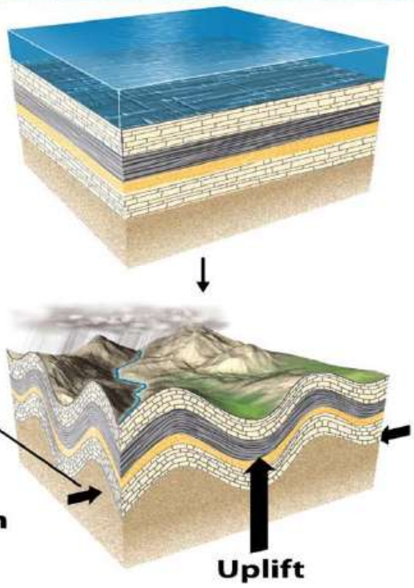
Subsidence below sea level allows a new layer, E, to be deposited over C. The irregular surface of C is preserved as an unconformity.



Angular Unconformity

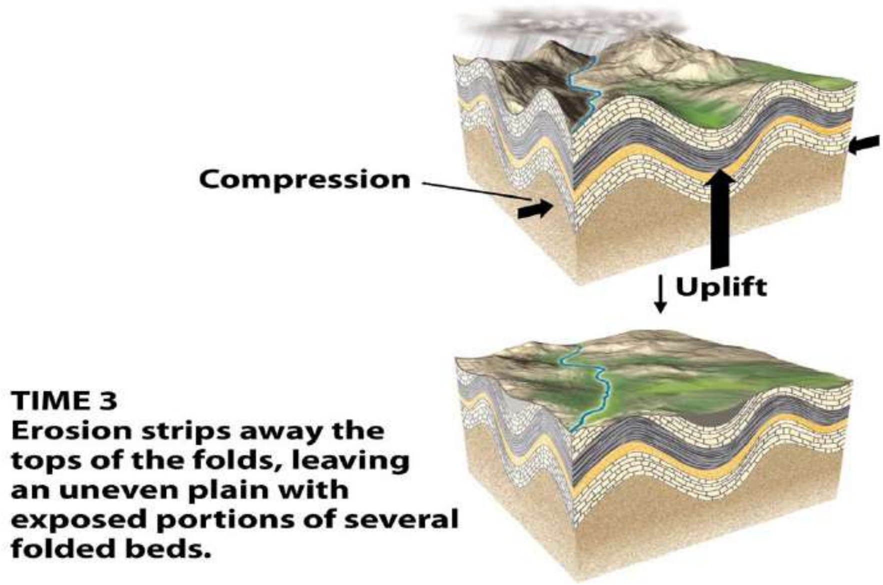
TIME 1
Beneath the ocean, sediments accumulate in beds.

Angular Unconformity

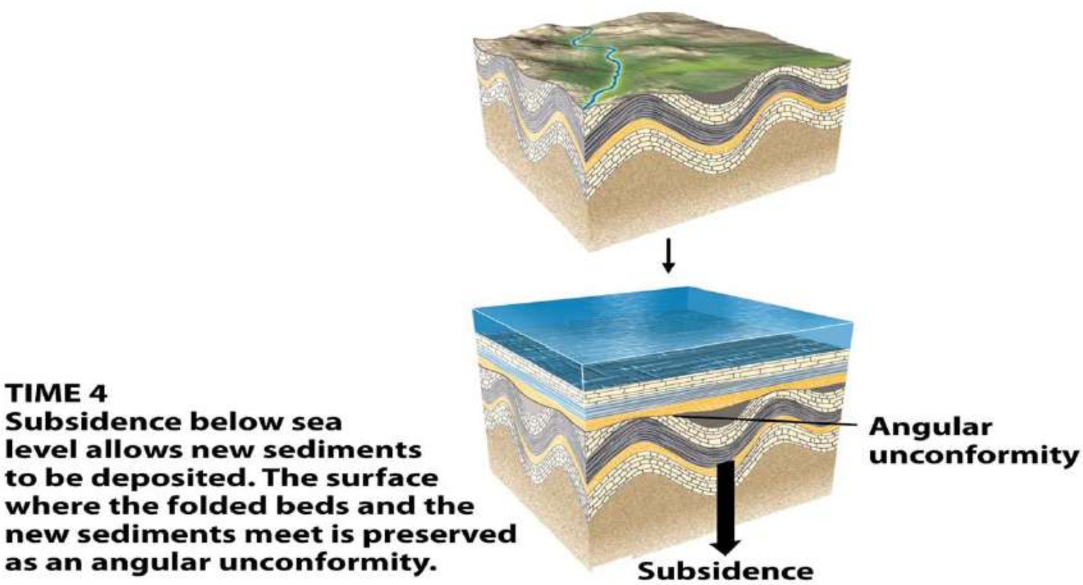


TIME 2
Later, tectonic forces cause uplift, folding, and deformation of the sedimentary beds.

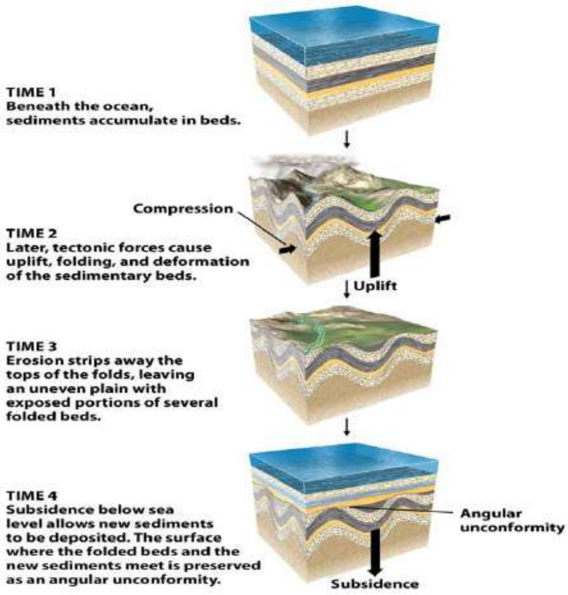
Angular Unconformity



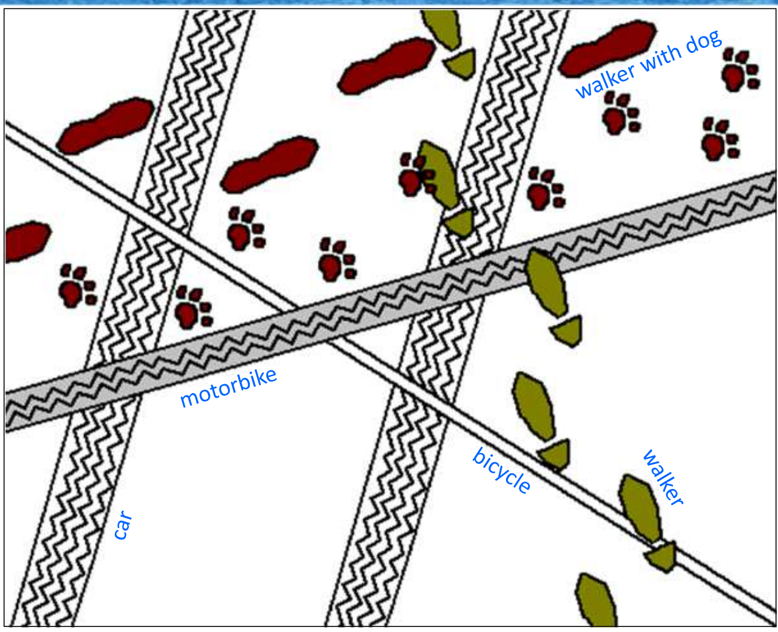
Angular Unconformity



Angular Unconformity



Cross-Cutting Relationship



walker with dog

walker

motorbike

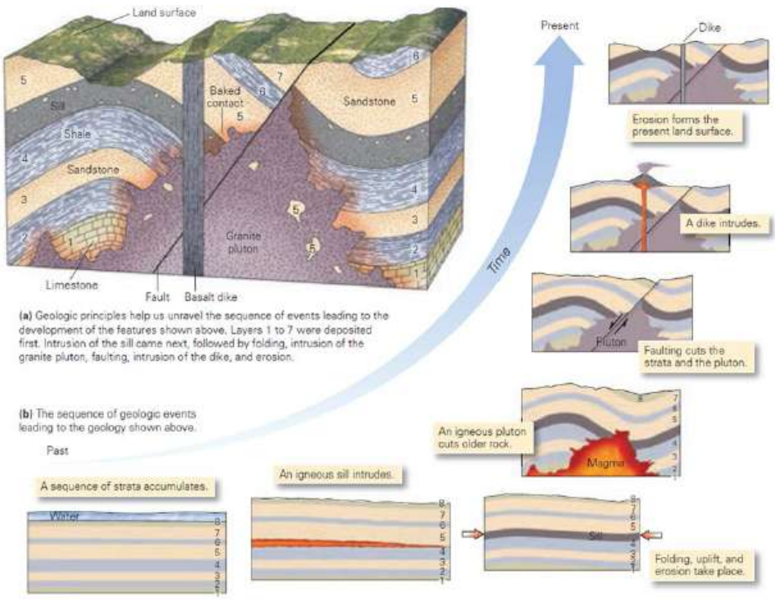
bicycle

car

Cross-Cutting Relationship

- The latest fracture movement should displace previous ones in a terrain with multiple generation of fractures.
- If the latest fracture involve shear component (Type -II), the previous fractures should slip accordingly along latest fracture.

Cross-Cutting Relationship



(a) Geologic principles help us unravel the sequence of events leading to the development of the features shown above. Layers 1 to 7 were deposited first. Intrusion of the sill came next, followed by folding, intrusion of the granite pluton, faulting, intrusion of the dike, and erosion.

(b) The sequence of geologic events leading to the geology shown above.

Next Lecture

Geological Time Scale (relative and absolute)

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 25. Geological Time Scale

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Geological Time Scale: relative and absolute (numerical) ages
- Biography of the Earth

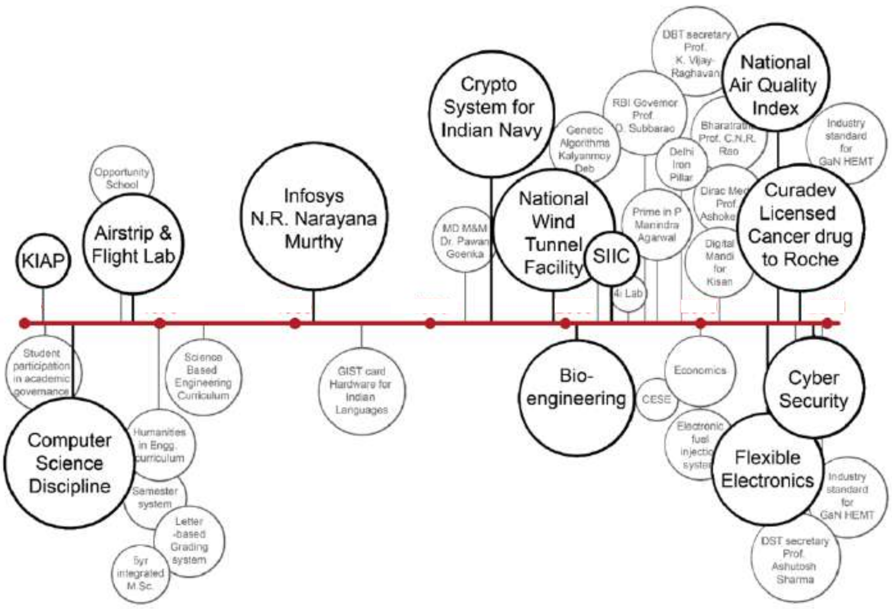
Reading:
Marshak's Book (Part-IV)
Grotinger & Jordan's book (Chapter 8)
[*for the entire week*]

Relative and absolute (numerical) ages

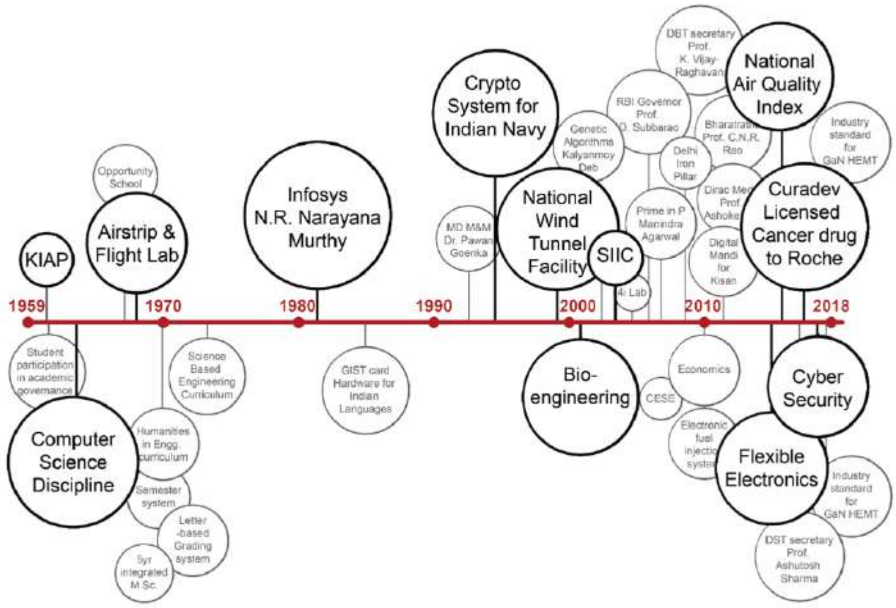
- Geologists studied the principles stratigraphic successions (previous lecture) and the Theory of Uniformitarianism (*physical processes we observe operating today also operated in the past, at roughly comparable rates* OR *present is the key to the past*) to determine the ***relative ages*** of the rocks structures, and other geologic features at a given location (Geologic Events).

- The relative ages cannot suggest time-line in the Earth history. of the rocks structures, and other geologic features at a given location (Geologic Events). This situation changed with the discovery of radioactivity. The overall determination and interpretation of numerical ages as **geochronology**. The technique of isotopic dating has been vastly improved over the years and we can now know more or less precisely the time-lines of the past geological events (***the Numerical Age***).

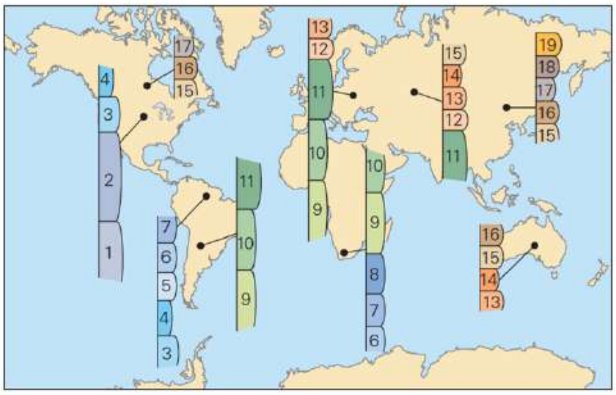
Relative timeline of IIT Kanpur



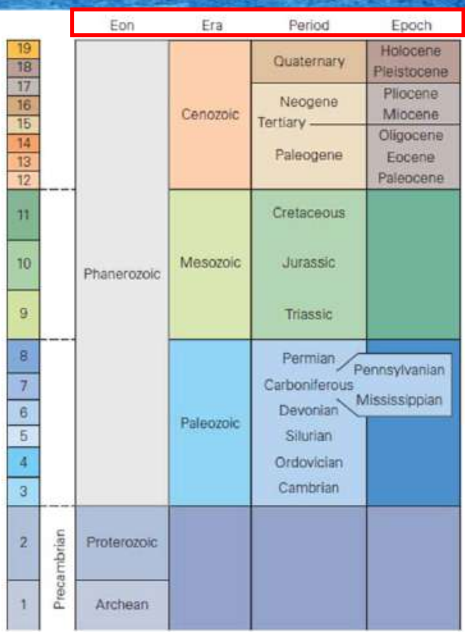
Absolute (numerical) timeline of IIT Kanpur



Relative Geological Time Scale



By correlating strata from locality to locality at millions of places around the world, geologists have pieced together a composite stratigraphic column, called the **geologic column**, that represents the entirety of Earth history.



Relative Geological Time Scale

EONS: The largest subdivisions break Earth's history into the *Hadean, Archean, Proterozoic*, and Phanerozoic—the first three of these, together, constitute the **Precambrian**.

- there is no rock record from Hadean

- *zoic* means LIFE, Proterozoic → first life; Phanerozoic → visible life

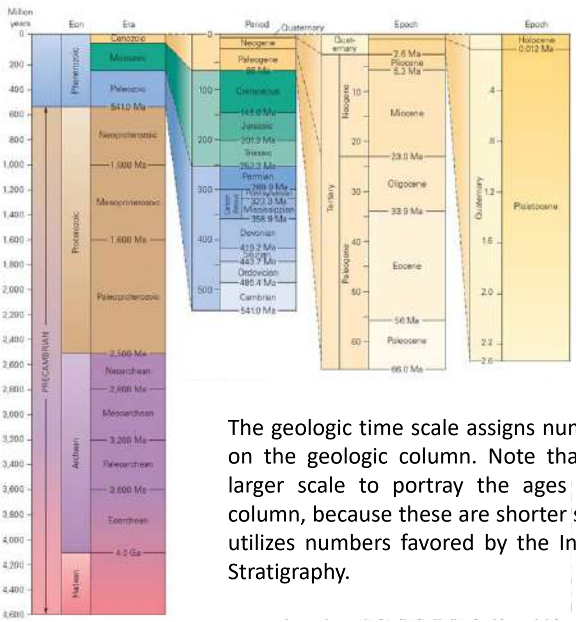
- because decades after the EONS had been named, geologists discovered that the earliest life, cells of bacteria and archaea, actually appeared during the Archean Eon.

ERAS: Eons are subdivided into **eras**. The Phanerozoic Eon, for example includes, in order from oldest to youngest, the Paleozoic (*ancient life*), Mesozoic (*middle life*), and Cenozoic (*recent life*) Eras.

Eras are further subdivided to **PERIODS** and each periods into **EPOCHS**.

- The names of the Periods are mostly from places where the signature rocks are best exposed

Absolute (Numerical) Geological Time Scale

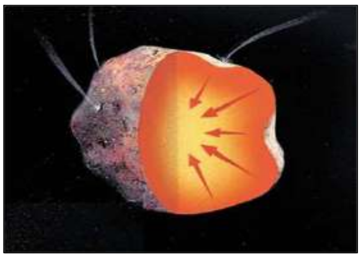


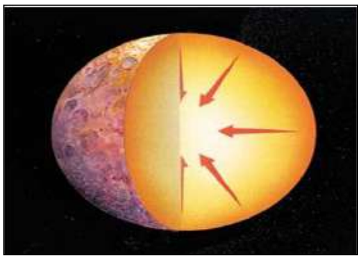
The geologic time scale assigns numerical ages to the intervals on the geologic column. Note that we have to change to a larger scale to portray the ages of intervals higher in the column, because these are shorter subdivisions. This time scale utilizes numbers favored by the International Commission on Stratigraphy.

Biography of the Earth

The Hadean Eon

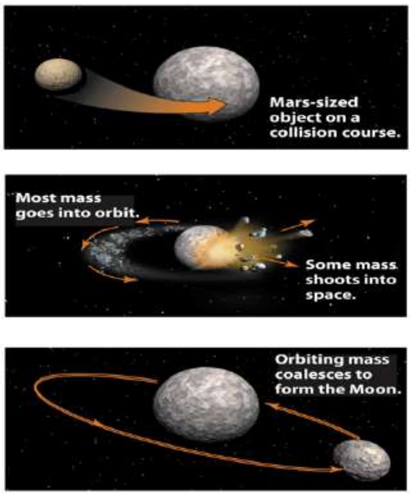
- The time between 4.57 and 3.8 Ga is the Hadean Eon.
  - Named for Hades, the Greek god of the underworld.
  - Began with formation of Earth by planetesimal accretion.
- Earth was heated by impacts and radioactive decay.
- Earth was hot enough to partially melt by ~ 4.5 Ga.
  - The molten Earth underwent chemical differentiation.
    - Gravity pulled molten iron into the center.
    - The ultramafic mantle remained as a thick shell.





The Hadean Eon

- After differentiation, Earth smashed a protoplanet.
- The size of Mars, this planet blasted…
  - A sizeable chunk of Earth's mantle.
  - Much of the protoplanet's mantle.
- Debris from the collision formed a ring around Earth.
- This debris coalesced to form the moon.
- When 1st formed, moon was much closer (20,000 km).
- Today it is 19x farther away (384,000 km).



The Hadean Eon

- Earth was inhospitable; a molten surface.
  - Evidence of solidified igneous rock dates from 4.4 Ga.
    - This evidence is from zircon grains, not a whole rock.
- Volcanic outgassing created a deadly atmosphere.
  - N_2, NH_3, CH_4, H_2O, CO, CO_2, and SO_4^{2-} were components.
  - This atmosphere had a greater density that today's.
- Early formed crust was bombarded by meteorites.
  - Meteorite impacts were abundant between 4.0 and 3.9 Ga.
    - This would have destroyed early formed crust.
    - Oldest evidence of crust is 4.03 Ga.
- The first oceans formed as rain from the skies.
  - Liquid water required cooling of the surface.
  - First evidence of oceans from marine sediments ~ 3.85 Ga.

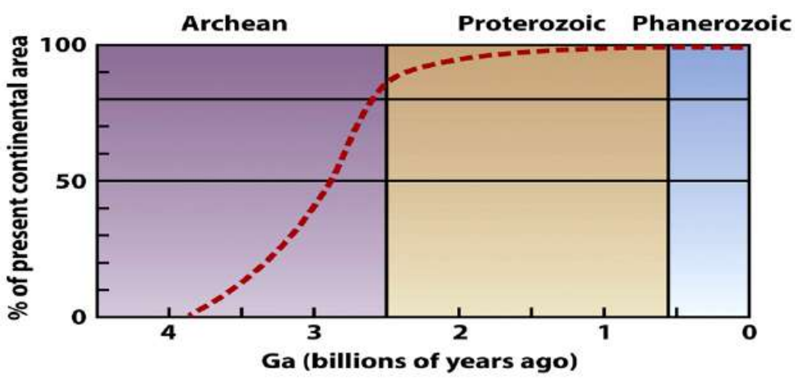
The Archean Eon

- Time of significant change to planet Earth.
- ~3.8 Ga, Earth had cooled to form lithosphere.
  - Intense meteorite bombardment ceased.
  - Portions of the rock record begin to survive.

- Had plate tectonics started yet? Two models:
  - Many small microplates, island arcs, and hot spot volcanoes rapidly formed and subducted crust.
  - Archean lithosphere was too hot to subduct; hot spot plume volcanics dominated formation of crust.

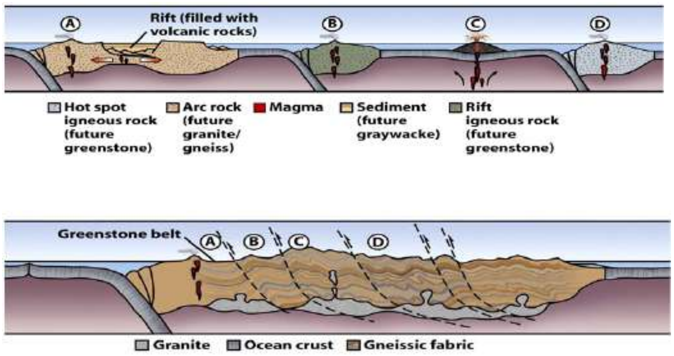
The Archean Eon

- Volume of continental crust increased dramatically.
  - 85% of modern continental area present by end of Archean.
  - Signals full development of plate tectonic processes.



The Archean Eon

- How did continental crust form?
  - Low-density felsic rocks formed above subduction zones.
    - Felsic crustal blocks grew via continental collision.
    - Felsic sediments accumulated near continental crust.
  - Mantle hot spots built mafic volcanoes.
  - Continental crust is too buoyant to subduct.
    - Jams subduction trenches.
    - Shuts off subduction.
    - Creates thickened, uplifted continental crust.
  - Frequent collisions sutured volcanic arcs, hot spots, and sedimentary debris together as protocontinents.



The Archean Eon

- Archean cratons consist of 5 principal rock types.
  - Gneiss – Hi-grade metamorphics from Archean collisions.
  - Greenstone – Metamorphosed fragments of mafic rocks.
  - Granite – Magmas from partial melting of the crust.
  - Graywacke – Sedimentary debris derived from arcs.
  - Chert – Silica precipitated in the deep sea.
- Archean shallow sediments are poorly known.
  - There were few shallow depositional settings, or…
  - Few examples have survived destruction by erosion.
- Sedimentary processes were clearly operating.
  - Transport rounded sediment grains.





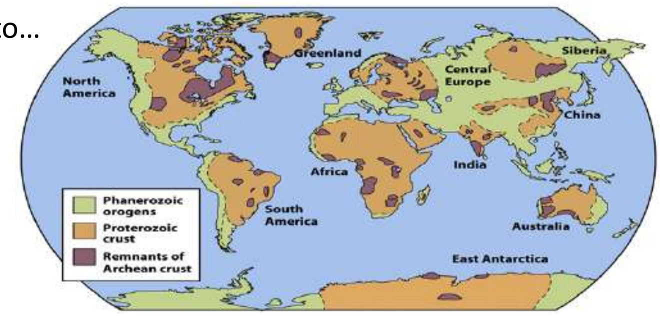
The Archean Eon

- Life first appeared during the Archean. Evidence?
  - Biomarker molecules; Isotopic signatures; Fossil cells.
- Clear evidence of life in rocks dated to 3.5 Ga.
  - Life may have started earlier.
- Oldest undisputed bacteria fossils ~ 3.2 Ga.
- Rocks after 3.2 Ga contain stromatolites.
  - Layered mats of cyanobacteria (blue-green algae).
  - Sediments stuck to mucous coatings on algal filaments.
- Photosynthesis changed Earth's atmosphere.
  - Converted CO_2 and H_2O to organic matter and free oxygen.

Khelen et al., 2017

The Proterozoic Eon

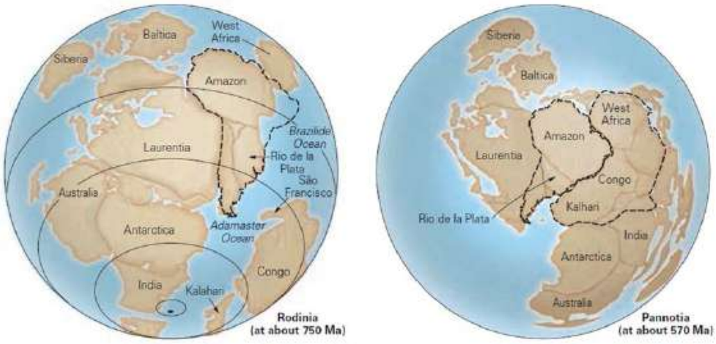
- Protero = first; zoic = life.
  - Named before Archean life was discovered.
- ~ 2 Ga (2.5 to 0.542 Ga); almost ½ of Earth history.
- The unfamiliar Archean world changed to…
  - Fewer, larger lithospheric plates.
  - Larger continental landmasses.
  - An oxygenated atmosphere.



- New continental crust formed, but at slower rates.
  - 90% of Earth's continental crust by the middle Proterozoic.
  - Continents grew by addition of volcanic arcs.
  - Continents cooled and strengthened to become cratons.

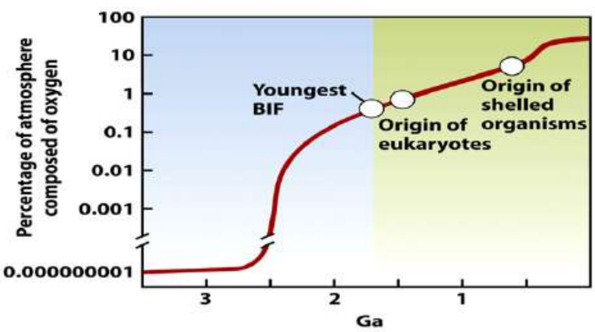
The Proterozoic Eon

- Continental collision created Precambrian supercontinents.
  - Rodinia – Formed ~ 1 Ga.
  - The Grenville orogeny formed an extensive mountain belt.
- Pannotia – A short-lived supercontinent ~ 570 Ma.



The Proterozoic Eon

- Atmospheric oxygen (O_2) skyrocketed 2.4 to 2.2 Ga.
  - Currently, O_2 is 21% of the atmosphere.
  - Before 2.2 Ga, detrital pyrite in sediments indicated no O_2.
  - Redbeds (red from Fe-oxides) don't appear before 2.2 Ga.
  - Banded iron formations (BIFs) – Fe dissolved in the ocean reacted with O_2, forming worldwide iron oxide deposits.

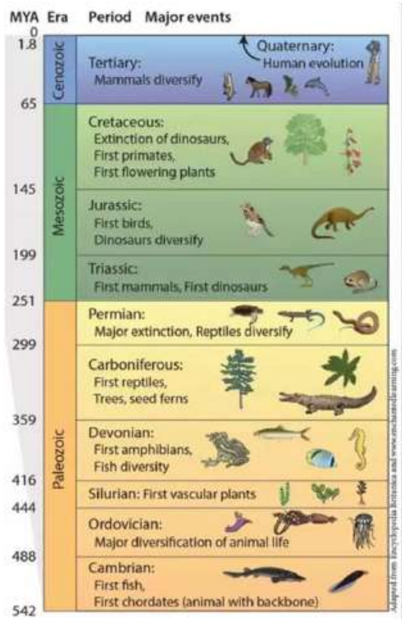


The Proterozoic Eon

- Atmospheric O_2 permitted diversification and multicellular of life (~500 Ma).
- Ediacaran fauna – Unusual soft-bodied fossils.
  - Preserved in end Proterozoic sediments; Multicellular invertebrates resembling worms and jellyfish.
  - Two events: assembly and break-up of Pannotia; Global cooling

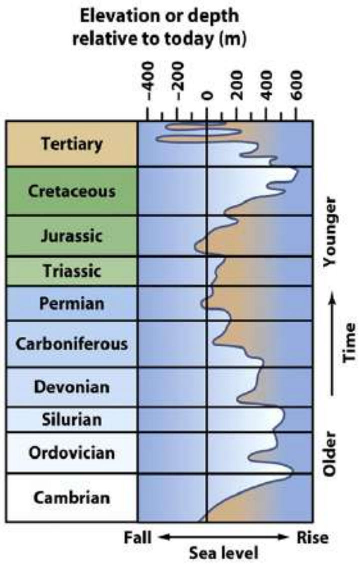
The Phanerozoic Eon

- Phaneros = visible; zoic = life.
- The most recent 542 Ma of Earth history.
  - Began with appearance of diverse hard-shelled organisms.
    - Hardshells vastly increased fossil preservation.
    - Made possible a more complete archive of life on Earth.
- The Phanerozoic is divided into 3 eras.
  - Paleozoic – Ancient life (Trilobites, Nautiloids).
  - Mesozoic – Middle life (Brachiopods, Dinosaurs).
  - Cenozoic – Recent life (early Horses, Mammoths..).
- Eras emphasize changes in Earth's biota.



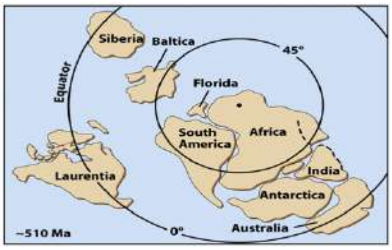
The Proterozoic Eon

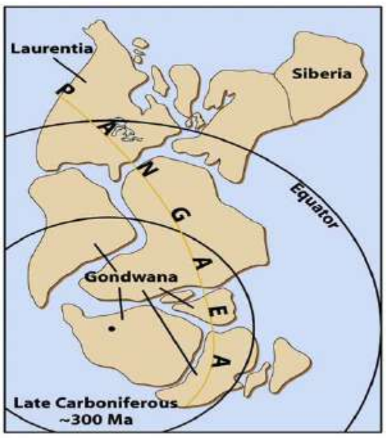
- Tectonic plates and continental blocks rearranged.
- New supercontinents formed and rifted apart.
- Numerous orogenic belts were created and eroded.
- Phanerozoic sea level (SL) has changed often.
- High sea level flooded continental interiors (sediment deposition).
- Low sea level exposed continental margins (erosion or nondeposition.)

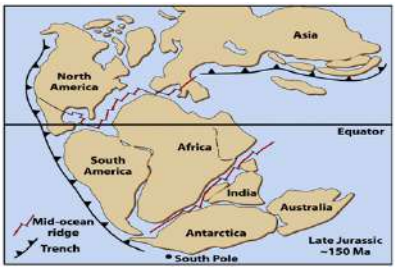


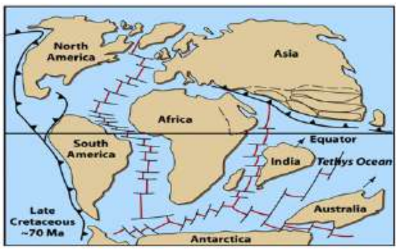
The Proterozoic Eon

- Rearrangements of the continents



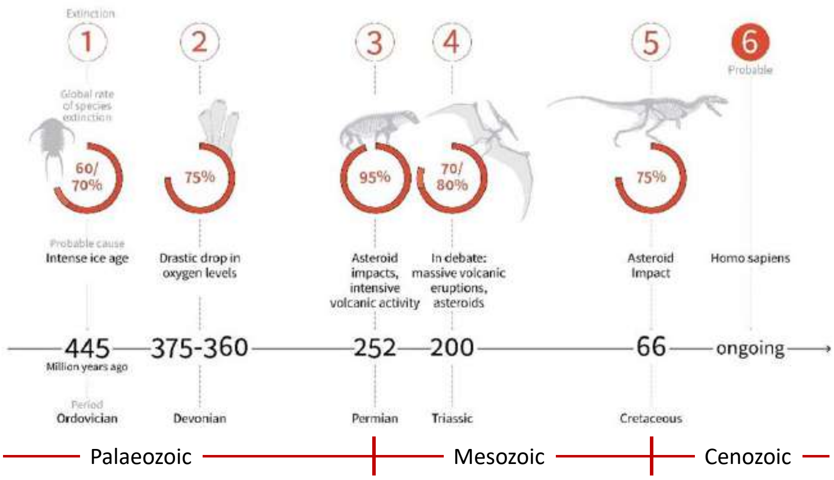






The Proterozoic Eon

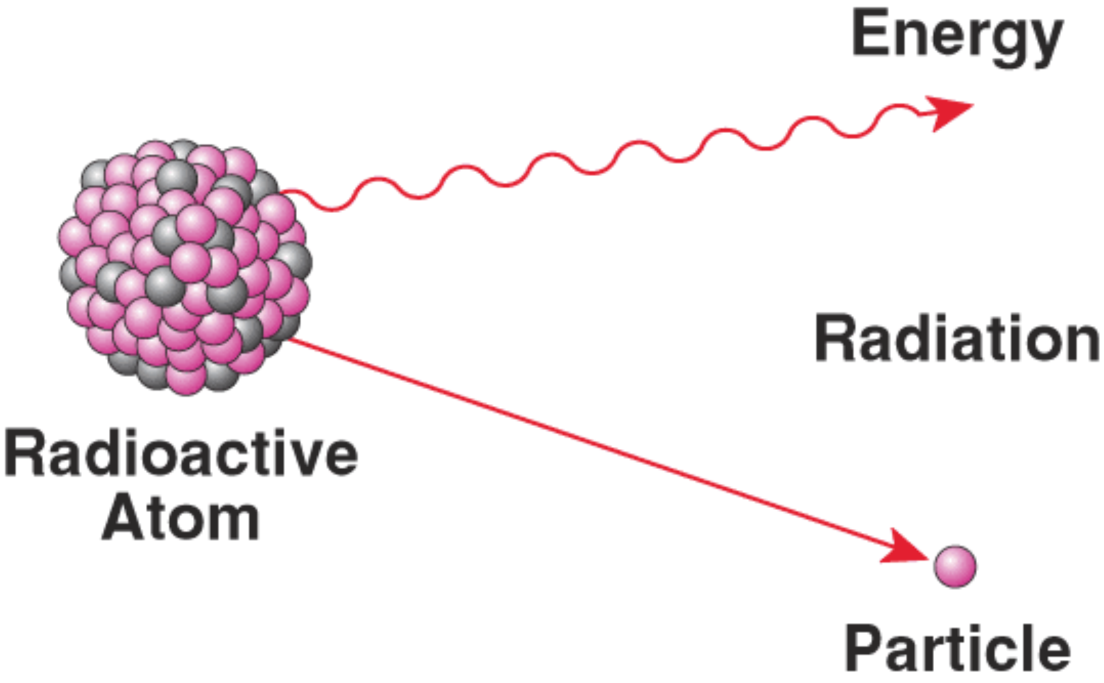
Global Mass extinctions
More than 99 % of all organisms that have ever lived on Earth are extinct.

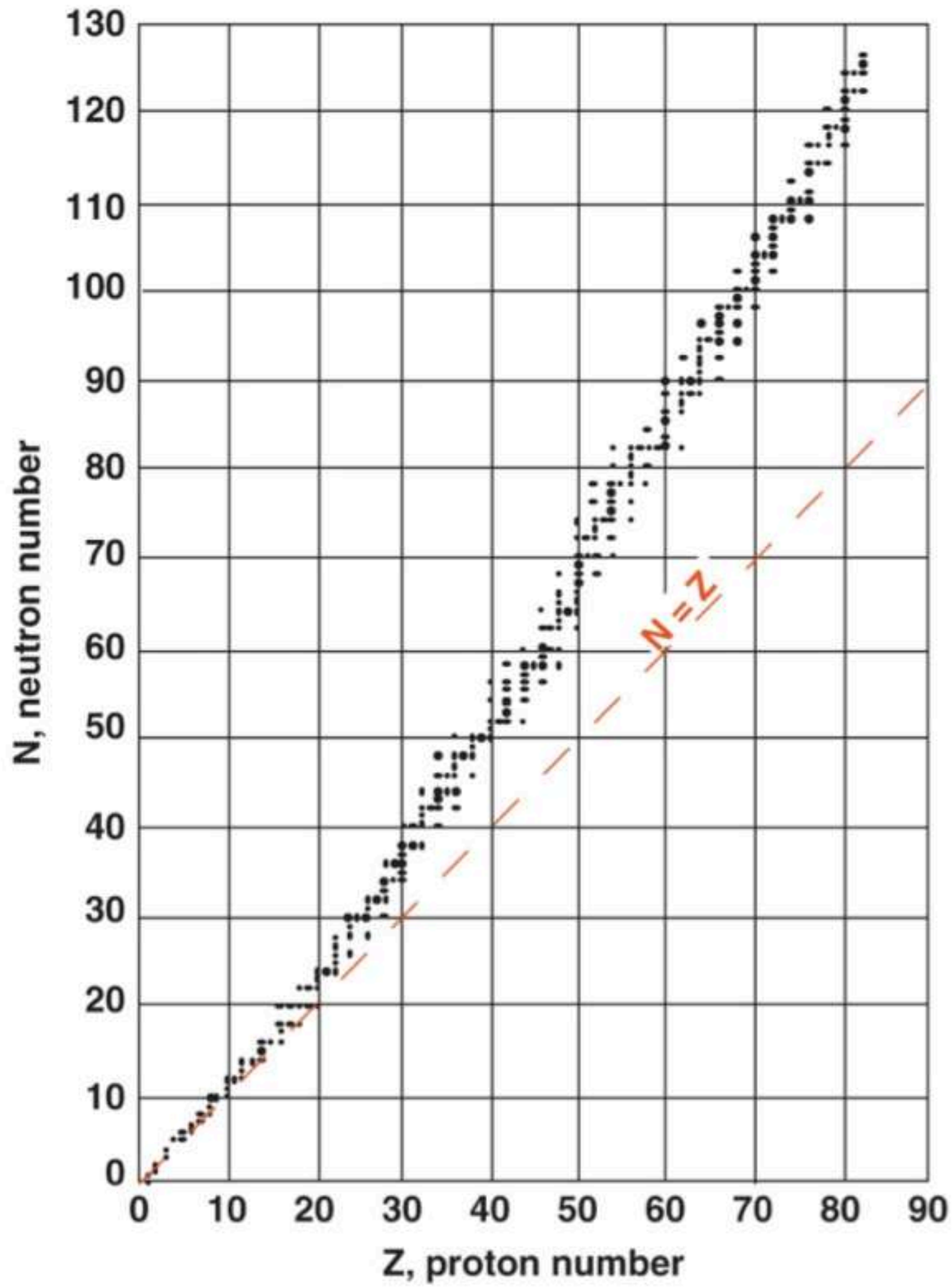


Next Lecture

Methods of Numerical Age Dating

Isotope Geochemistry




130
120
110
100
90
80
70
60
50
40
30
20
10
0
N, neutron number
0
10
20
30
40
50
60
70
80
90
Z, proton number
N = Z

I-b Properties of nuclides

- Mass:

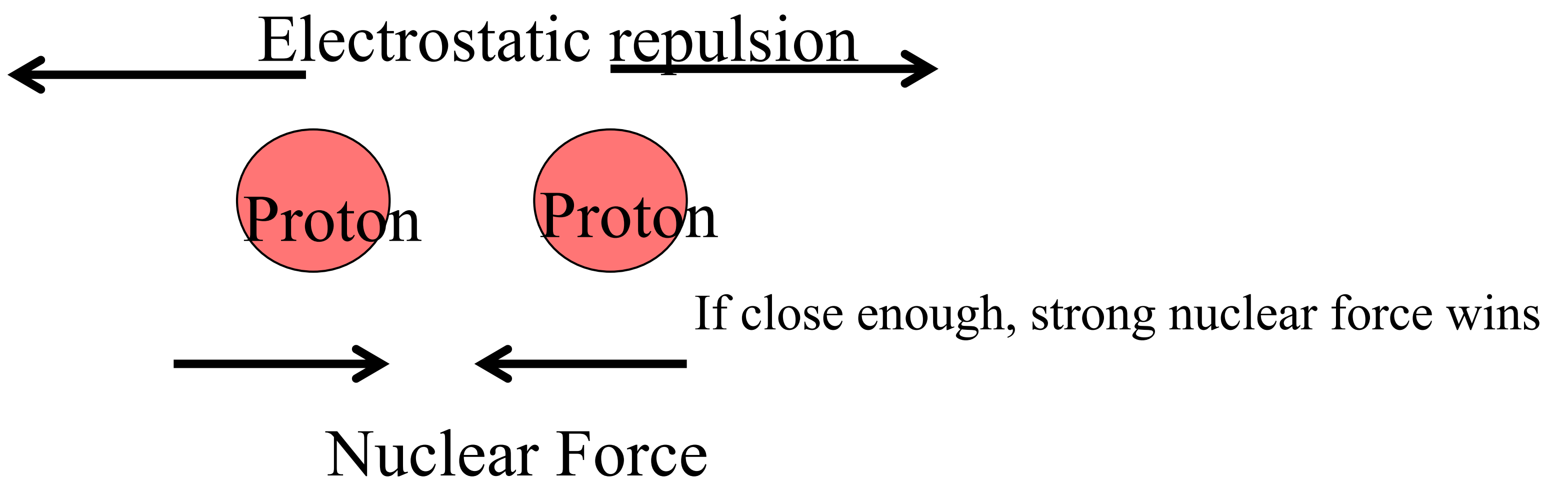
The mass of a nuclide is given in amu (atomic mass unit)

Definition: $M(^{12}C)=12$ amu

$m_{proton} \approx m_{neutron} \approx 1$ amu

- The mass of one atom of carbon 12 (12C) is determined by mass spectrometry and is equal to 1.9922×10^{-23} g

- Electrostatic repulsion vs. nuclear attraction



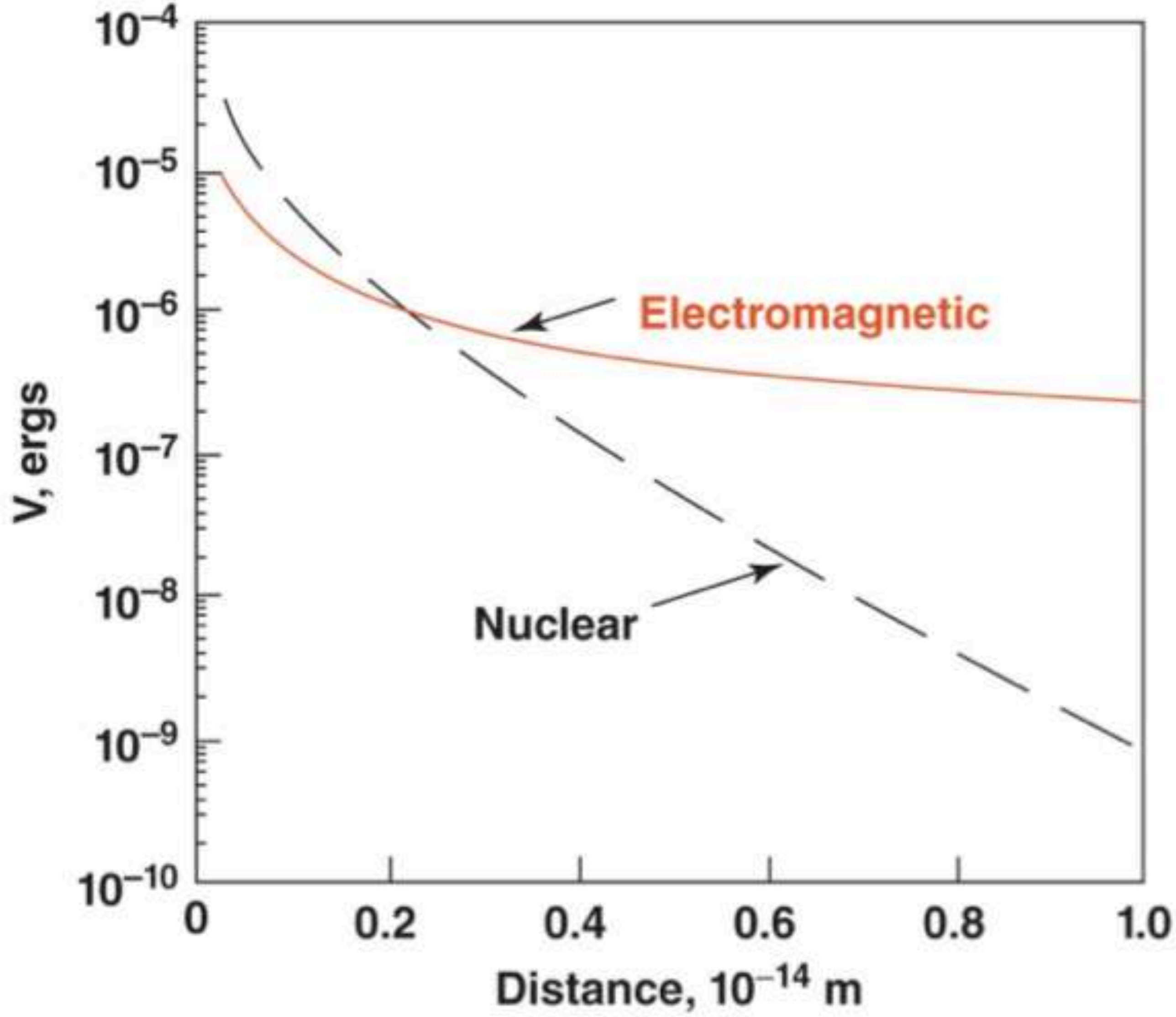
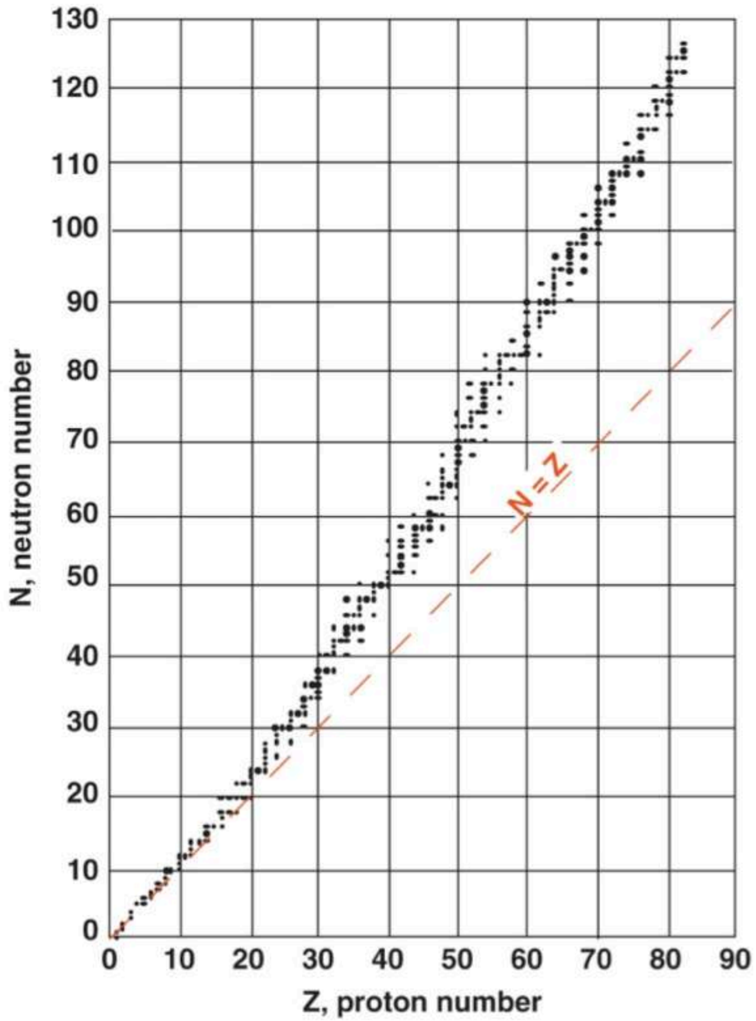


Figure 1.2 The nuclear and electromagnetic potential of a proton as a function of distance from the proton.



The elements deviate from the 1:1 line.

As the number of protons increases in a nucleus, the electromagnetic force increases faster than the strong nuclear force. Therefore larger atoms needs more and more neutrons to remain stable.

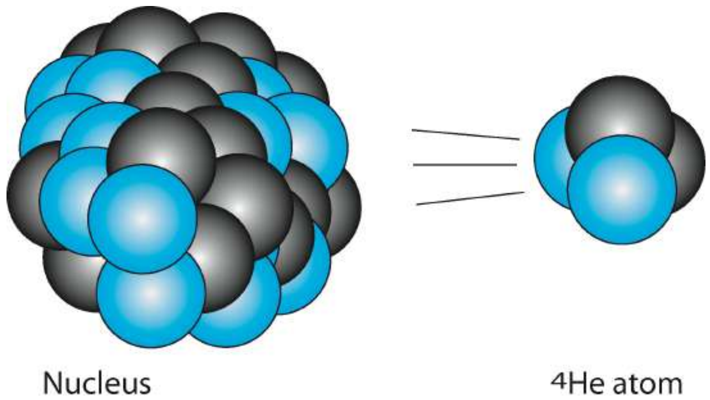
II. Natural Radioactivity

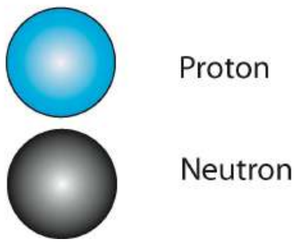
- Radioactivity is the emission of particles from unstable nuclei. Radioactivity allows a nucleus to evolve from an unstable state to a more stable configuration.

- The emitted particles by radioactivity are of three types: α, β, γ.
  α= ^4He nucleus;
  β^-= electron or β^+= positron;
  γ= photons

α– decay

- Occurs for unstable nuclides with A ≥ 56 (except ^{5}He, ^{5}Li and ^{6}Be)
- Consists of 2 proton and 2 neutron



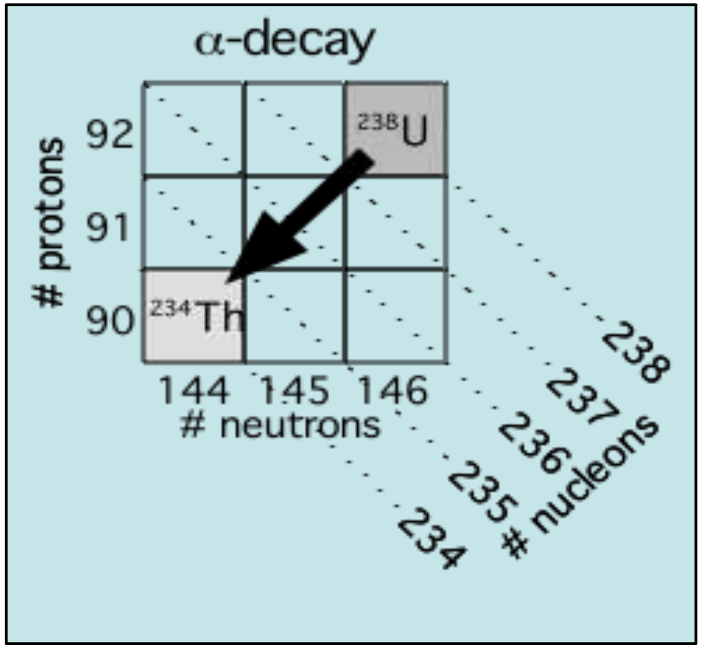


	Atomic No.	*Neutron No.*	*Mass No.*
Parent	Z	N	Z+N =A
Daughter	Z-2	N-2	Z-2+N-2 = A-4

$$^{238}_{92}U = \,^{234}_{90}Th + \,^{4}_{2}He + \text{Energy}$$

α– decay

Emission of an α particle $= {}^4He$ nucleus (2 neutrons, 2 protons)



The number of nucleons A decreases by 4 and its Z by 2.

Example: ${}^{238}U \rightarrow {}^{234}Th + {}^4He$

Mass balance:

${}^{238}U$	238.0508 amu
${}^{234}Th$	–234.0436 amu
${}^4He$	–4.00260 amu

Mass defect 0.0046 amu

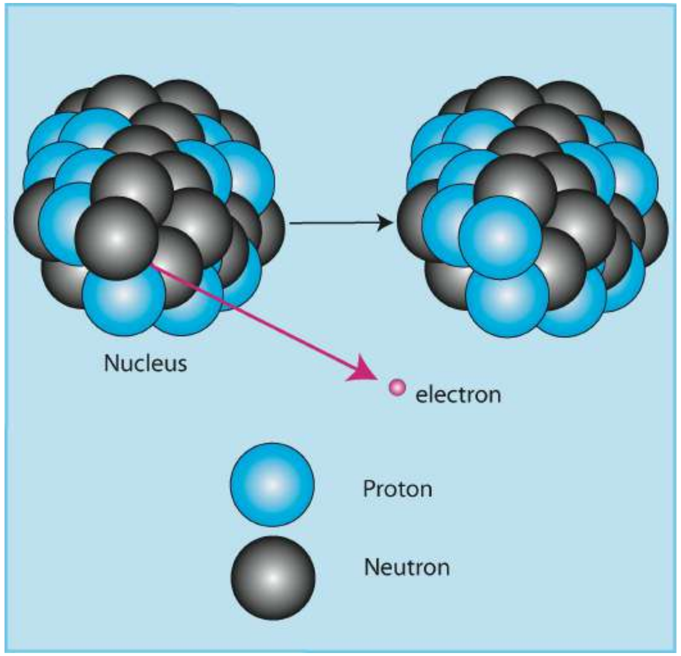
$= 6.86 \times 10^{-10}$ J/decay

$= 1.74 \times 10^{12}$ J/g ${}^{238}U$

=~480,000 KW-H (1.6 Billion BTUs)

This is the principal mode of decay of heavy isotopes such as U, Th, ${}^{209}Bi$

β^- decay



Decay by emitting a negatively charged beta particle

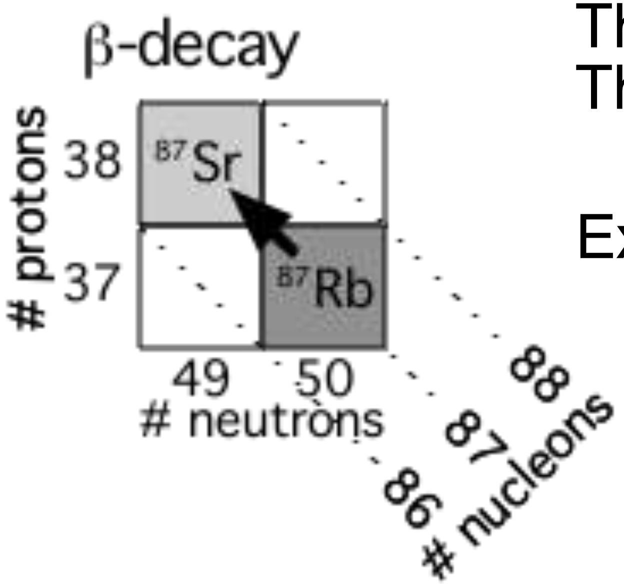
Neutron = Electron and Proton

	Atomic No.	*Neutron No.*	*Mass No.*
Parent	Z	N	Z+N =A
Daughter	Z+1	N-1	Z+1+N-1 = A

$${}^{40}_{19}\mathrm{K} = {}^{40}_{20}\mathrm{K} + \text{Energy}$$

β^- decay

Emission of an electron (and an antineutrino) during the conversion of a neutron to a proton



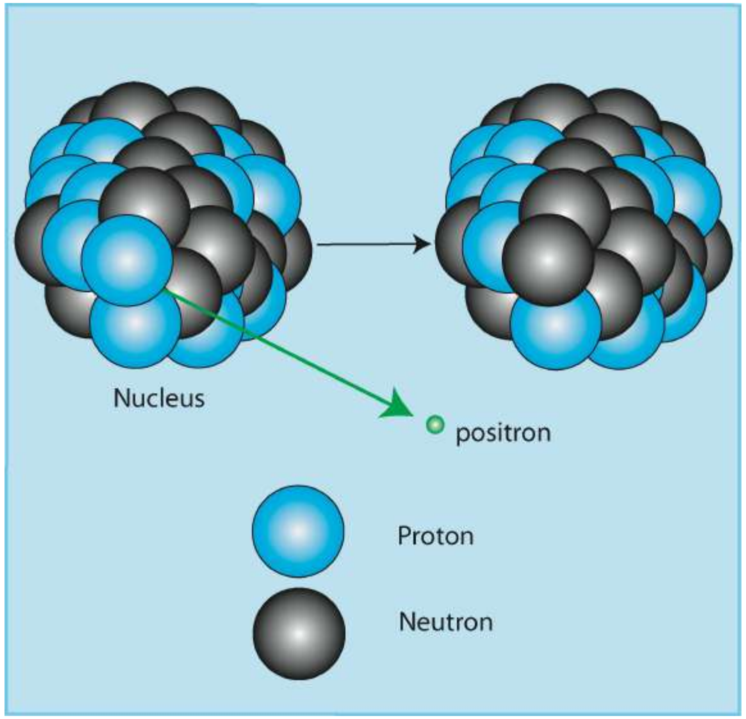
The number of nucleons does not change.
The atomic number increase by one:

Example: $^{87}Rb \rightarrow {}^{87}Sr + e^- + \bar{\nu}$

This is the preferred mode of decay for nuclei with an excess number of protons relative to the stability valley.

β^+ decay and electron capture

- A proton transforms into a neutron with emission of a positron and a neutrino:

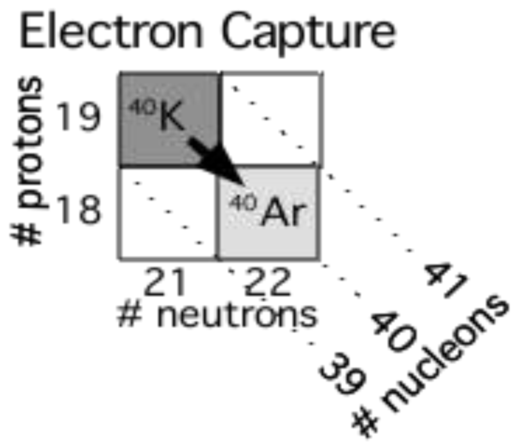


$$p \rightarrow n + e^{+} + \nu$$

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^{+} + \bar{\nu}$$

β^+ decay and electron capture

Emission of a positron (and a neutrino) *or* capture of an electron from an internal layer. This is the conversion of a proton into a neutron



The number of nucleons does not change. The atomic number decreases by one :

Examples: $^{40}_{19}K \text{->} ^{40}_{18}Ar + e^- + \nu$

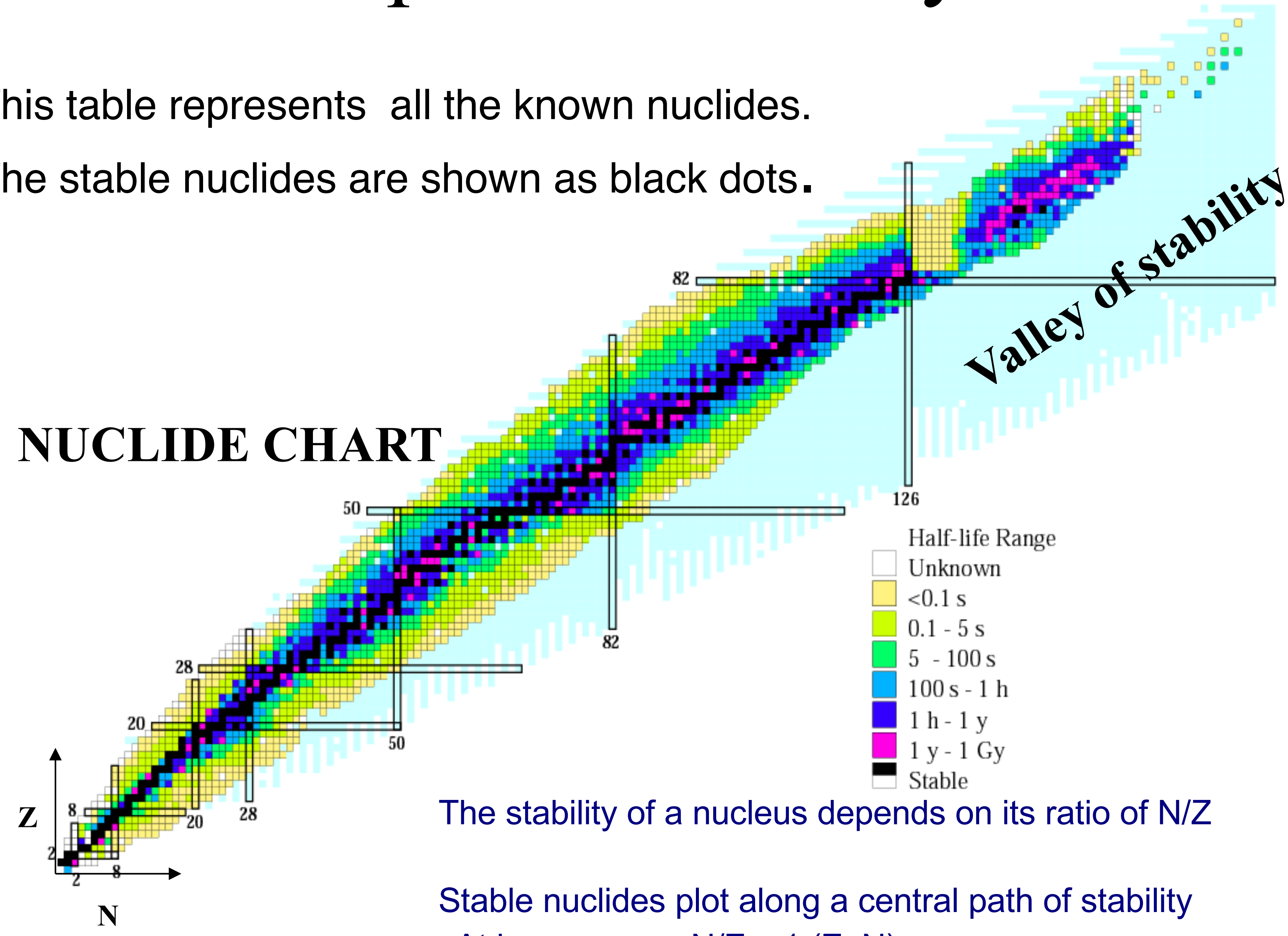
These are the decay mode for nuclei with an excess of protons relative to the stability valley.

Central path of stability

This table represents all the known nuclides.

The stable nuclides are shown as black dots.

NUCLIDE CHART



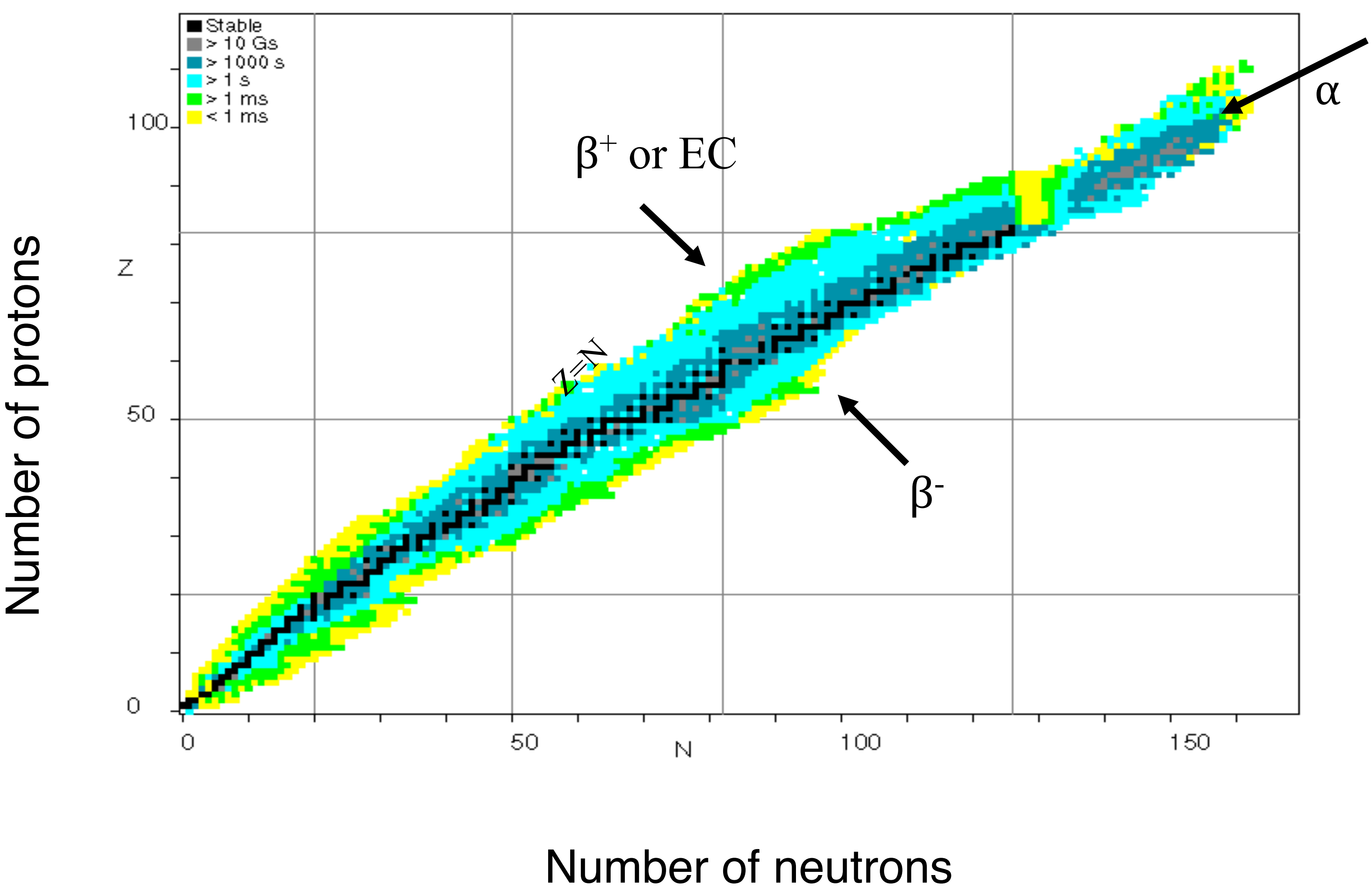
The stability of a nucleus depends on its ratio of N/Z

Stable nuclides plot along a central path of stability

At low masses, N/Z ≈ 1 (Z=N)

At high masses, N/Z ≈ 3

NUCLIDE CHART

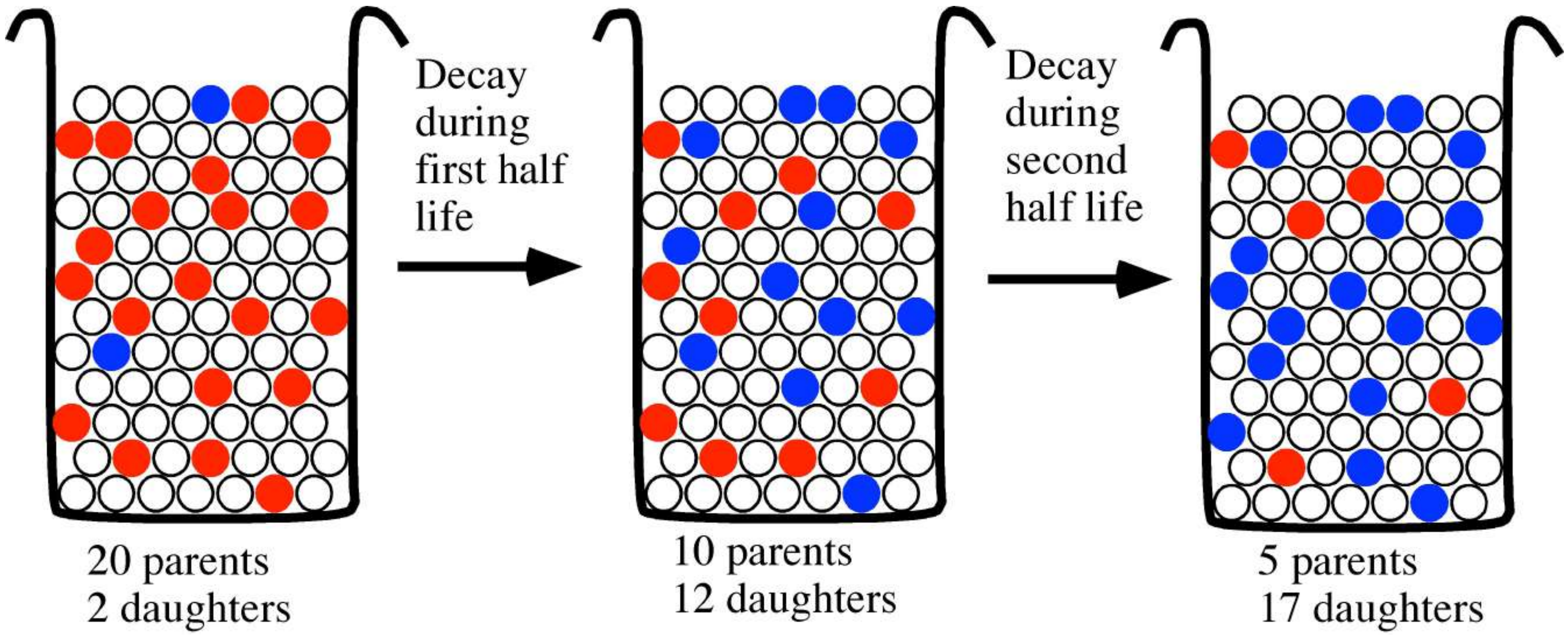


Isotopes

Radiogenic Isotopes Geochemistry

Stable Isotopes Geochemistry

Dating with Radioactivity



The actual number of atoms that decay (radioactive parent) continually decreases and the number of stable daughter atoms (radiogenic daughter) increases.

Simple Radioactive Decay

Radioactive decay is a stochastic process linked to the stability of nuclei. The rate of change in the number of radioactive nuclei is a function of the total number of nuclei present and the decay constant λ.

$$- dN / dt = \lambda N$$

The sign on the left hand is negative because the number of nuclei is decreasing. Rearranging this equation yields

$$- dN / N = \lambda dt$$

and integrating yields

$$- \ln N = \lambda t + C$$

C is the integration constant. We solve for C by setting $N = N_0$ and $t = t_0$. Then

$$C = - \ln N_0$$

Substituting for C gives

$$- \ln N = \lambda t - \ln N_0$$

We rearrange

$$\ln N - \ln N_0 = - \lambda t$$

Rearrange again

$$\ln N/N_0 = - \lambda t$$

Eliminate the natural log

$$N/N_0 = e^{-\lambda t}$$

And rearrange

$$N = N_0 e^{-\lambda t}$$

…continue…

Unfortunately, we don't know N_0 a priori, but decayed N have produced radiogenic daughters D*.

Therefore $D^* = N_0 - N$

Replacing N_0 with $N\,e^{\lambda t}$ yields $D^* = N\,e^{\lambda t} - N$

Rearranged $D^* = N\,(e^{\lambda t} - 1)$ or, for small λ t, $D^* = N\,\lambda\,t$,

The number of daughter isotopes is the sum of those initially present plus those radiogenically produced.

$$D = D_0 + D^*$$

Therefore, $D = D_0 + N\,(e^{\lambda t} - 1)$ or, for small λ t, $D = D_0 + N\,\lambda\,t$,

This is the basic radioactive decay equation used for determining ages of rocks, minerals and the isotopes themselves. D and N can be measured and λ has been experimentally determined for nearly all known unstable nuclides. The value D_0 can be either assumed or determined by the **isochron method**.

How to obtain a "half-life"?

The rate of decay of a radioactive parent nuclide to a stable daughter product is proportional to the number of nuclides present at any time (Rutherford and Sody, 1902)

$$\frac{dN}{dt} = -\lambda N \quad (1)$$

whereby N is number of nuclides , t is time and λ is the decay constant

Integration of 1

$$\int_{N_0}^{N} \frac{dN}{dt} = -\lambda \int_0^t dt$$

results in

$$\ln \frac{N}{N_0} = -\lambda t \quad (2)$$

which can be rewritten as

$$N = N_0 e^{-\lambda t} \quad (3)$$

Half life: $N=N_0/2$ and $t=t_{1/2}$

$$t_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$

Points to Remember

$$-dN/dt = \lambda N$$

N= # atoms of the radioactive nuclide, t = time,
λ = decay constant = probability that an atom will decay in a unit time

$$N = N_0 e^{-\lambda t}$$

$N_0 = N$ at $t=0$

$$t_{1/2} = (\ln 2) / \lambda = .693/\lambda$$

Half-life = time it takes for half a sample to decay (t when $N = \frac{1}{2} N_0$)

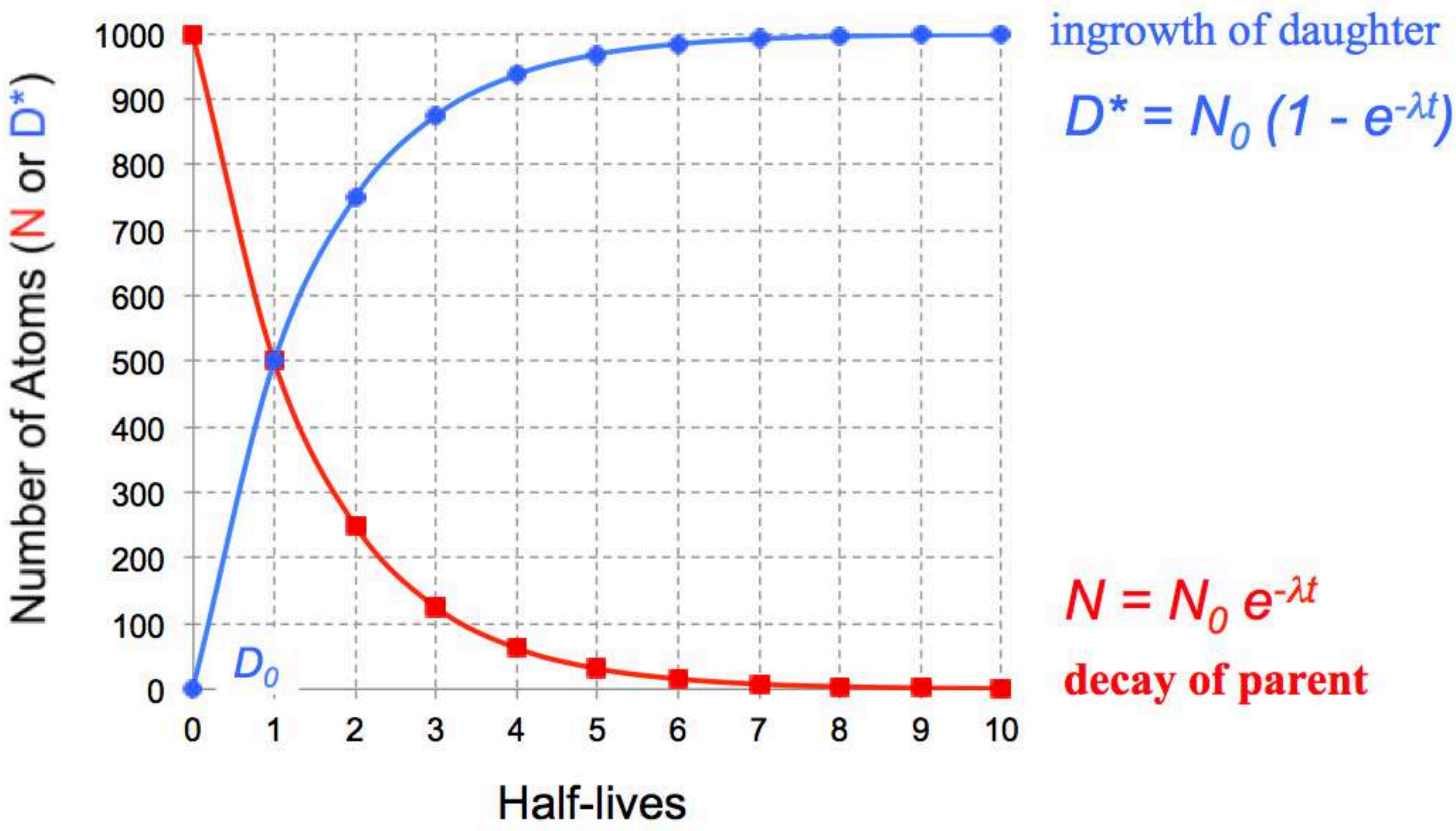
$$D = D_0 + N(e^{\lambda t} - 1)$$

D* = radiogenic daughter = # daughter atoms produced by radioactive decay of a parent, P ($D = D_0 + D^*$)

Divide by a stable, non-radiogenic isotope of the daughter element to get ratios e.g. for $^{87}Rb \rightarrow {}^{87}Sr + \beta^-$:

$$^{87}Sr/^{86}Sr = (^{87}Sr/^{86}Sr)_0 + {}^{87}Rb/^{86}Sr\ (e^{\lambda t} - 1)$$ [Example]

Simple Decay: Radioactive Parent ⇒ Stable Daughter



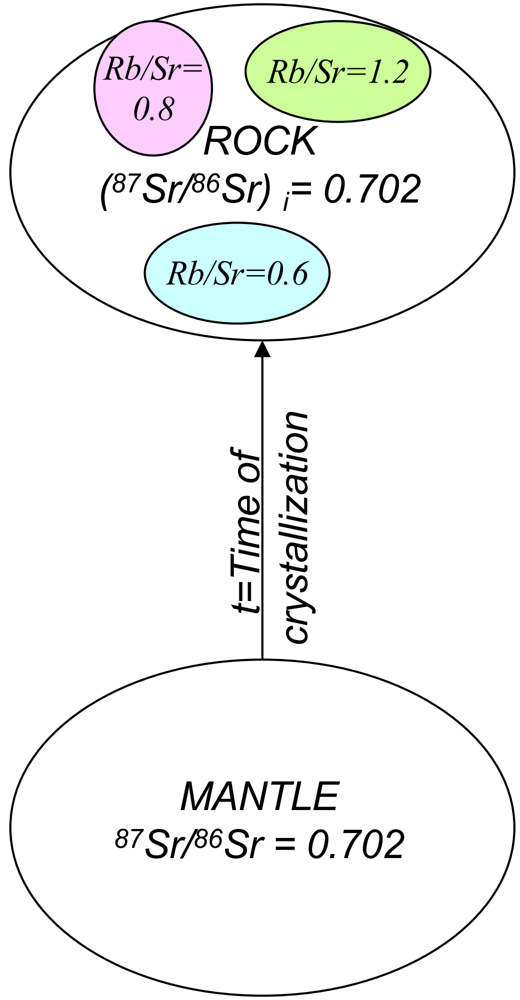
^{87}Rb-^{87}Sr decay equation (widely used in river geochemistry)

$$\frac{^{87}Sr}{^{86}Sr} = \left(\frac{^{87}Sr}{^{86}Sr}\right)_i + \frac{^{87}Rb}{^{86}Sr}(e^{\lambda t} - 1)$$

measured

measured

when you crystallize a rock, you will always have some Sr present



Uses of Radiogenic Isotopes

- Age Determination
- Source Identification
- Mixing Calculation

Dating

We can use the radioactive decay equation to calculate the age of a sample. We can measure the present day ratios and λ, but we still have 2 unknowns: R_0 and t. What can we do?

1) Assume zero initial daughter. This approach can be valid if you know something about mineralogy. For example, zircons are often used for U-Pb dating because the mineral incorporates U, but not lead. Therefore any Pb measured is radiogenic. Similarly, micas accept Rb but not Sr. Another example is K-Ar dating of volcanic rocks. Ar, the daughter, is lost upon eruption, and the only Ar present is radiogenic Ar.

2) Use 2 different isotope systems. For example, if you know what the age should be from a system where you think you know the initial daughter ratio (e.g. U-Pb), you can calculate the initial daughter ratio.

3) Assume one and calculate the other. If we assume the initial ratio and calculate an age, it is called a "Model Age"

4) Use an isochron diagram

The Isochron

The radioactive decay equation is in the form of a line:

$D = D_0 + P(e^{\lambda t}-1)$ … $y = b + xm$

Plot D ratio vs. P/D for several comagmatic or cogenetic samples and draw a best fit line through the data

y-intercept = initial D ratio, slope is related to t

This line is called an "**Isochron**"

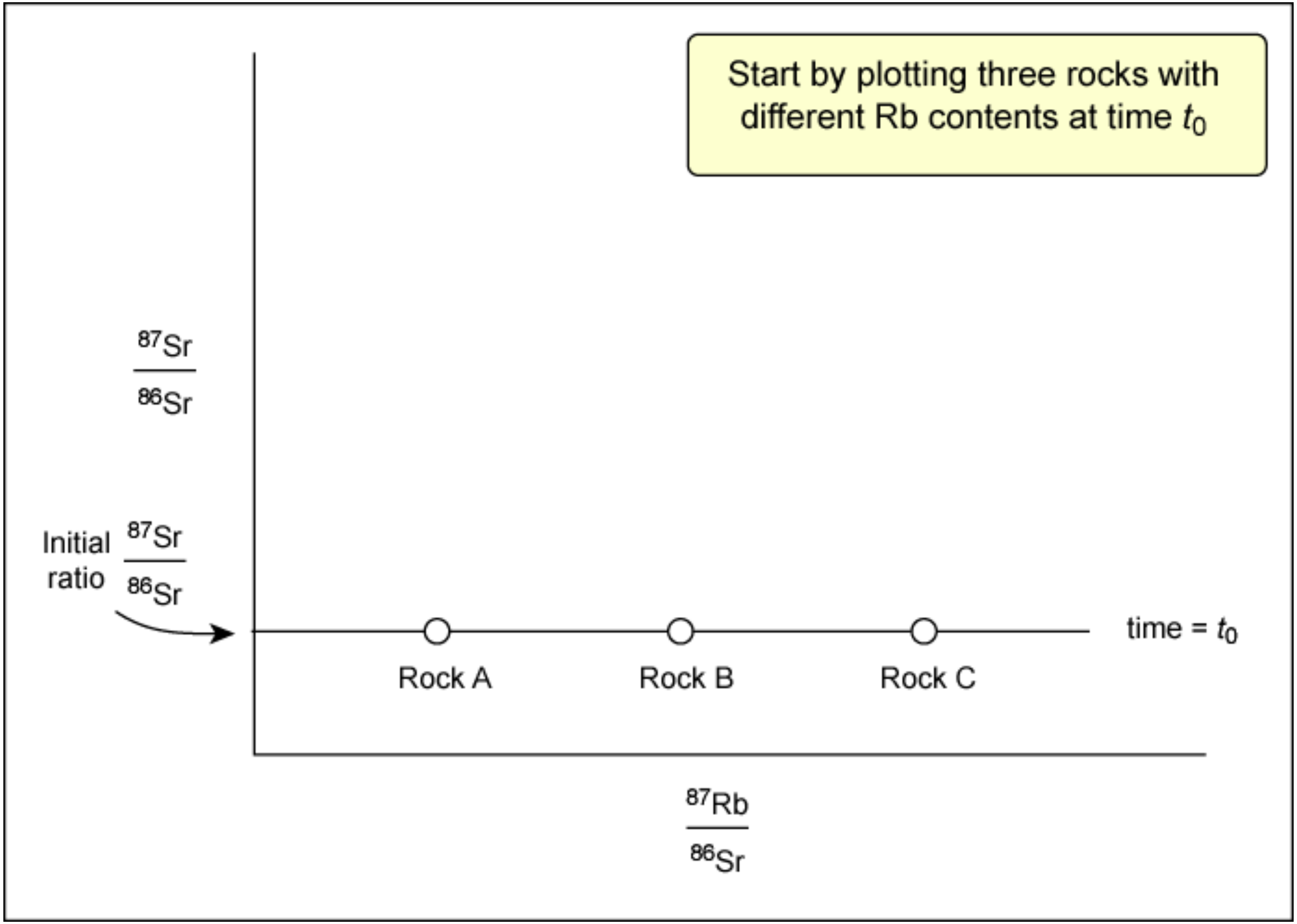
Represents true age if:

(1) The system was at isotopic equilibrium at time *t* = 0. I.e. all the samples formed with the same initial daughter isotope ratio

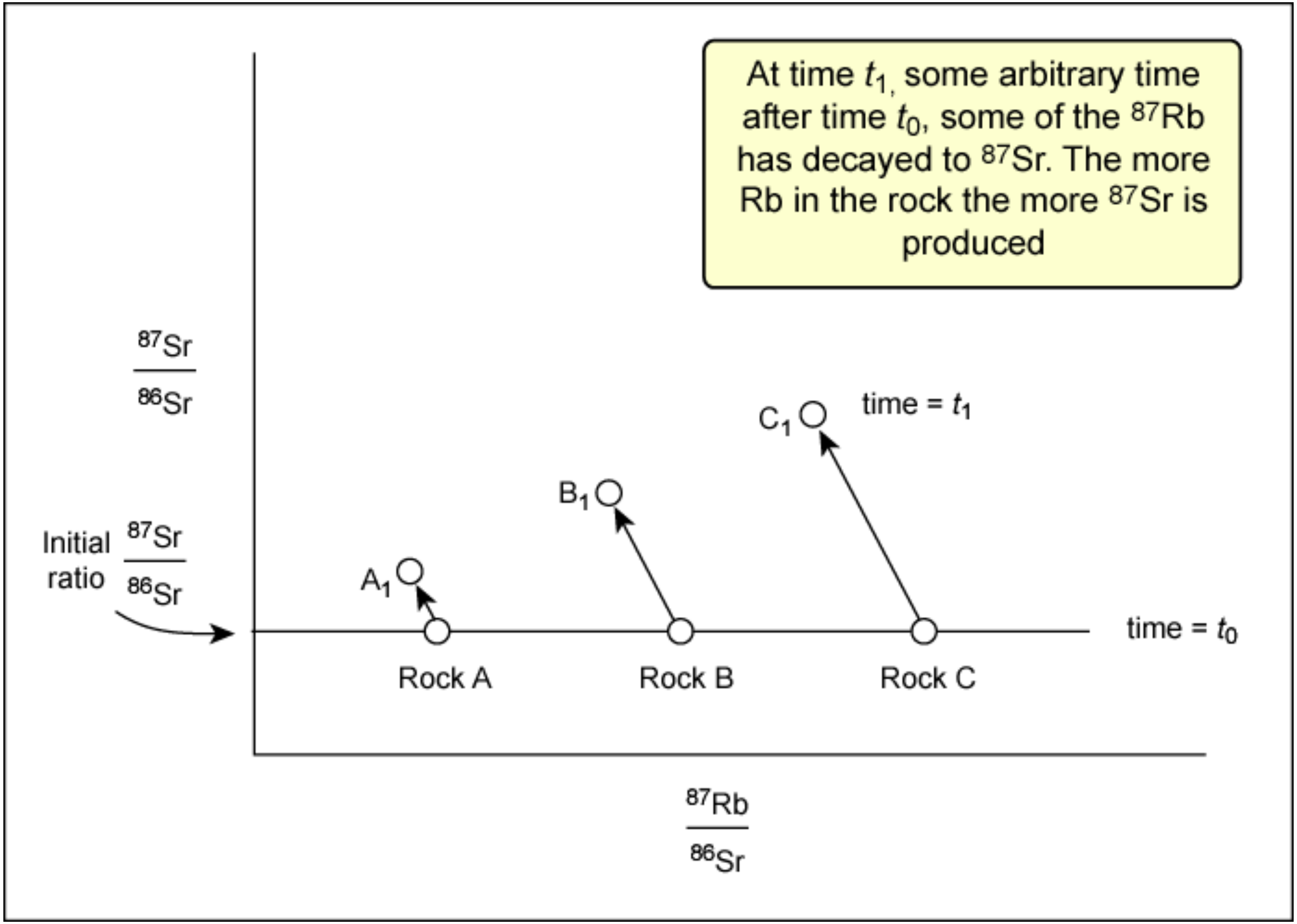
(2) Closed system since formation

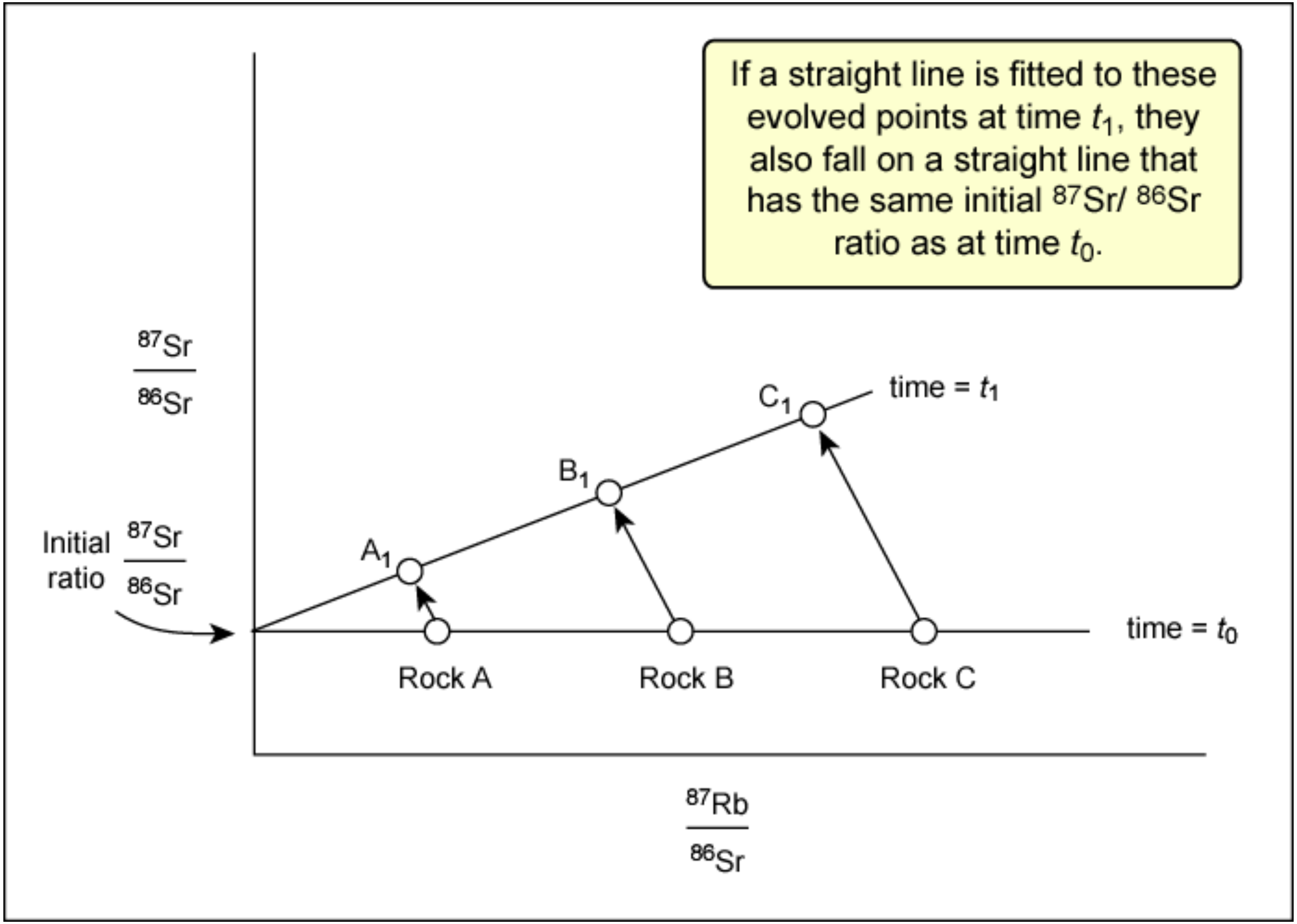
Whole-rock isochron represents age of formation

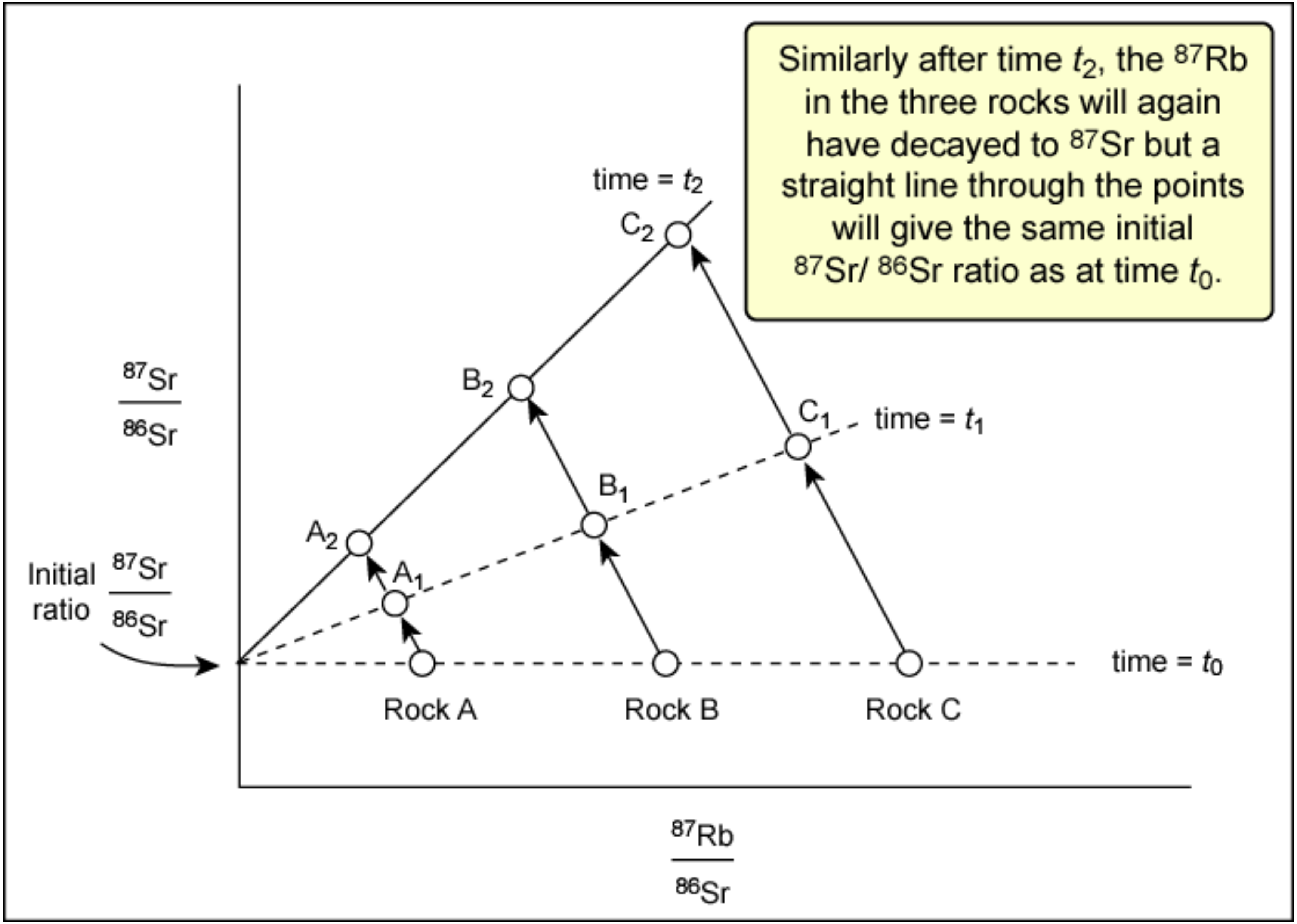
Mineral isochron represents age of last metamorphosis



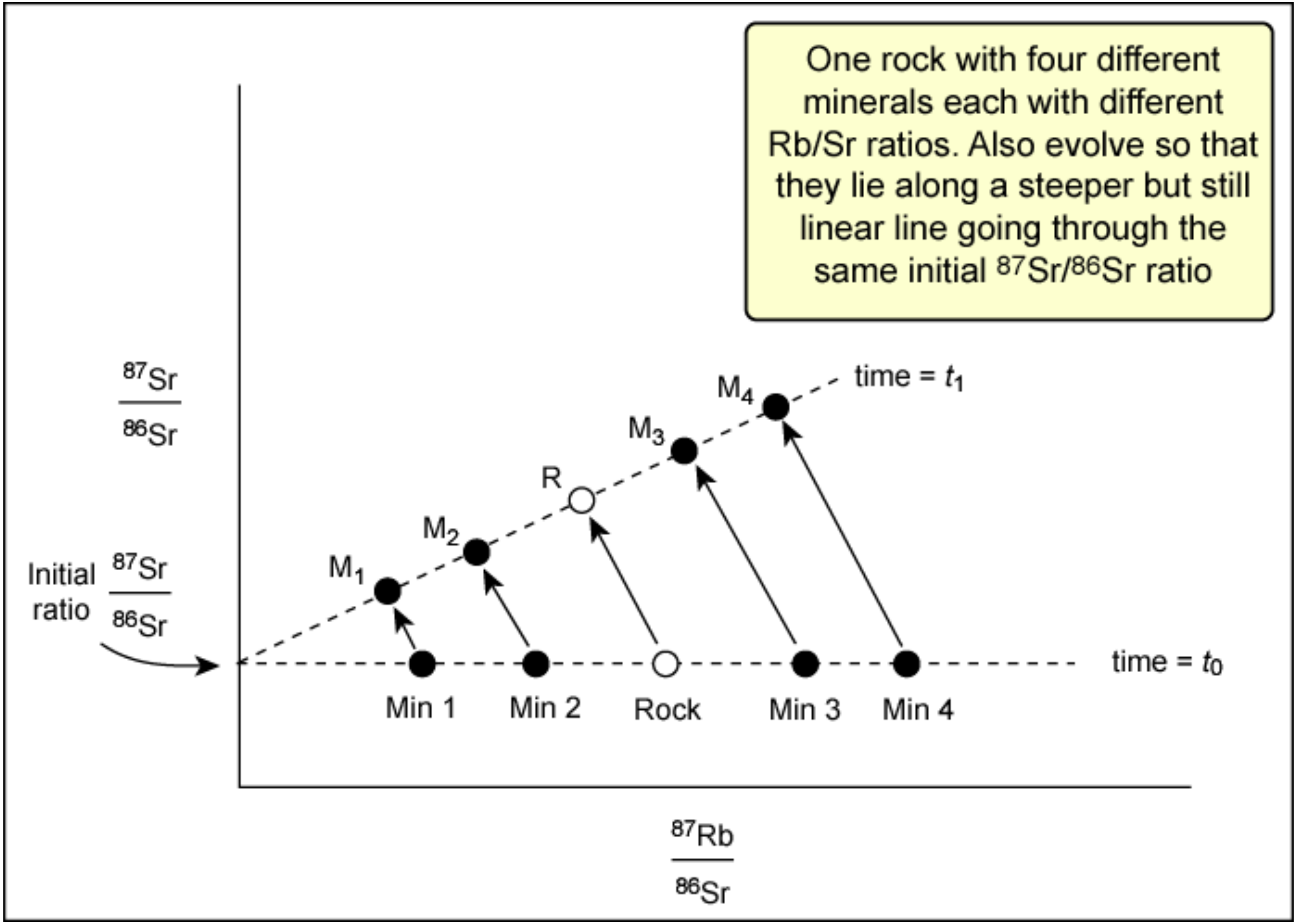
Start by plotting three rocks with different Rb contents at time t_0
$\frac{^{87}Sr}{^{86}Sr}$
Initial ratio $\frac{^{87}Sr}{^{86}Sr}$
time = t_0
Rock A
Rock B
Rock C
$\frac{^{87}Rb}{^{86}Sr}$


At time t_1, some arbitrary time after time t_0, some of the ^{87}Rb has decayed to ^{87}Sr. The more Rb in the rock the more ^{87}Sr is produced
$\frac{^{87}Sr}{^{86}Sr}$
Initial ratio $\frac{^{87}Sr}{^{86}Sr}$
A_1
B_1
C_1
time = t_1
time = t_0
Rock A
Rock B
Rock C
$\frac{^{87}Rb}{^{86}Sr}$


If a straight line is fitted to these evolved points at time t_1, they also fall on a straight line that has the same initial $^{87}Sr/^{86}Sr$ ratio as at time t_0.
$\frac{^{87}Sr}{^{86}Sr}$
Initial ratio $\frac{^{87}Sr}{^{86}Sr}$
A_1
B_1
C_1
time = t_1
time = t_0
Rock A
Rock B
Rock C
$\frac{^{87}Rb}{^{86}Sr}$

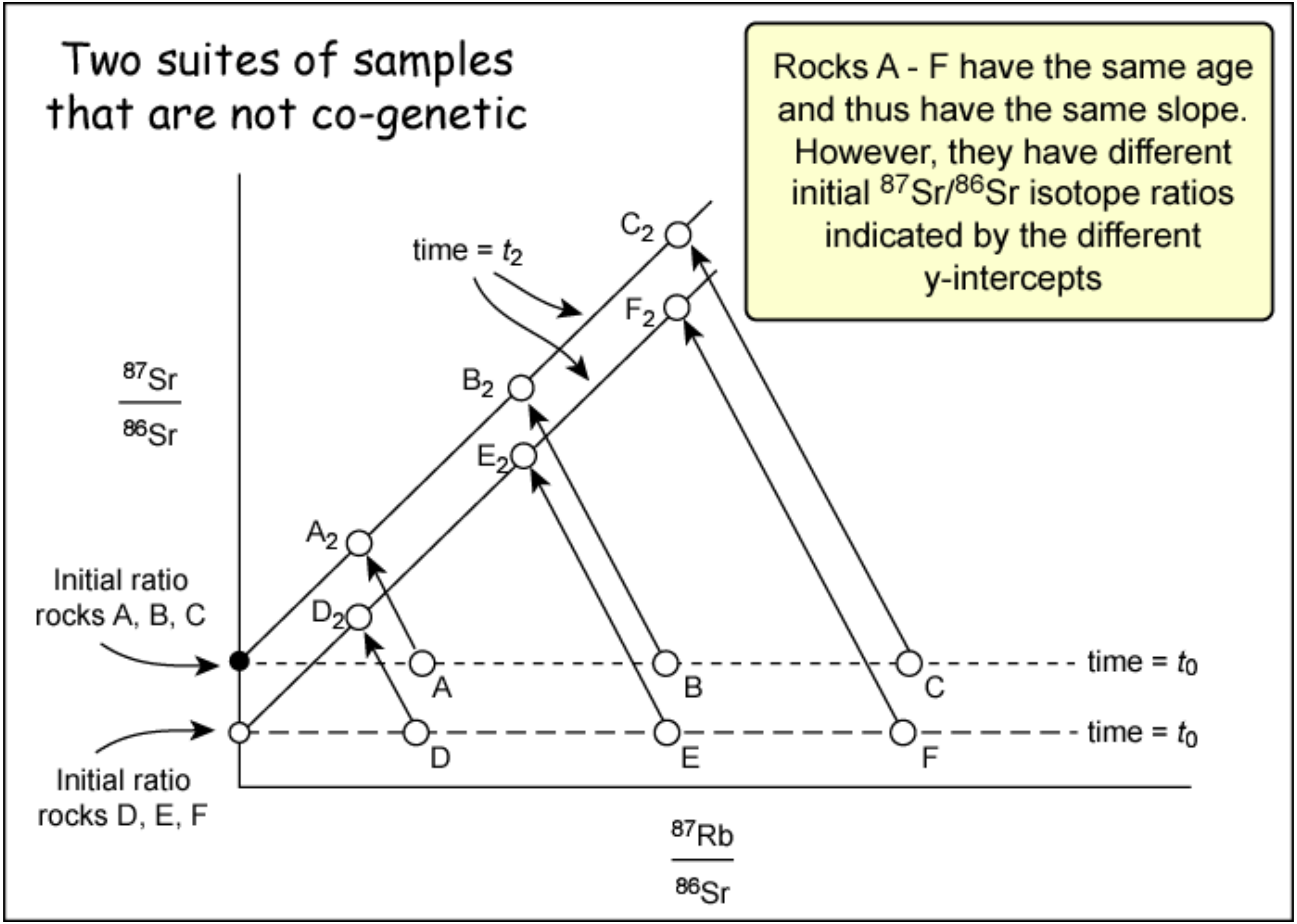


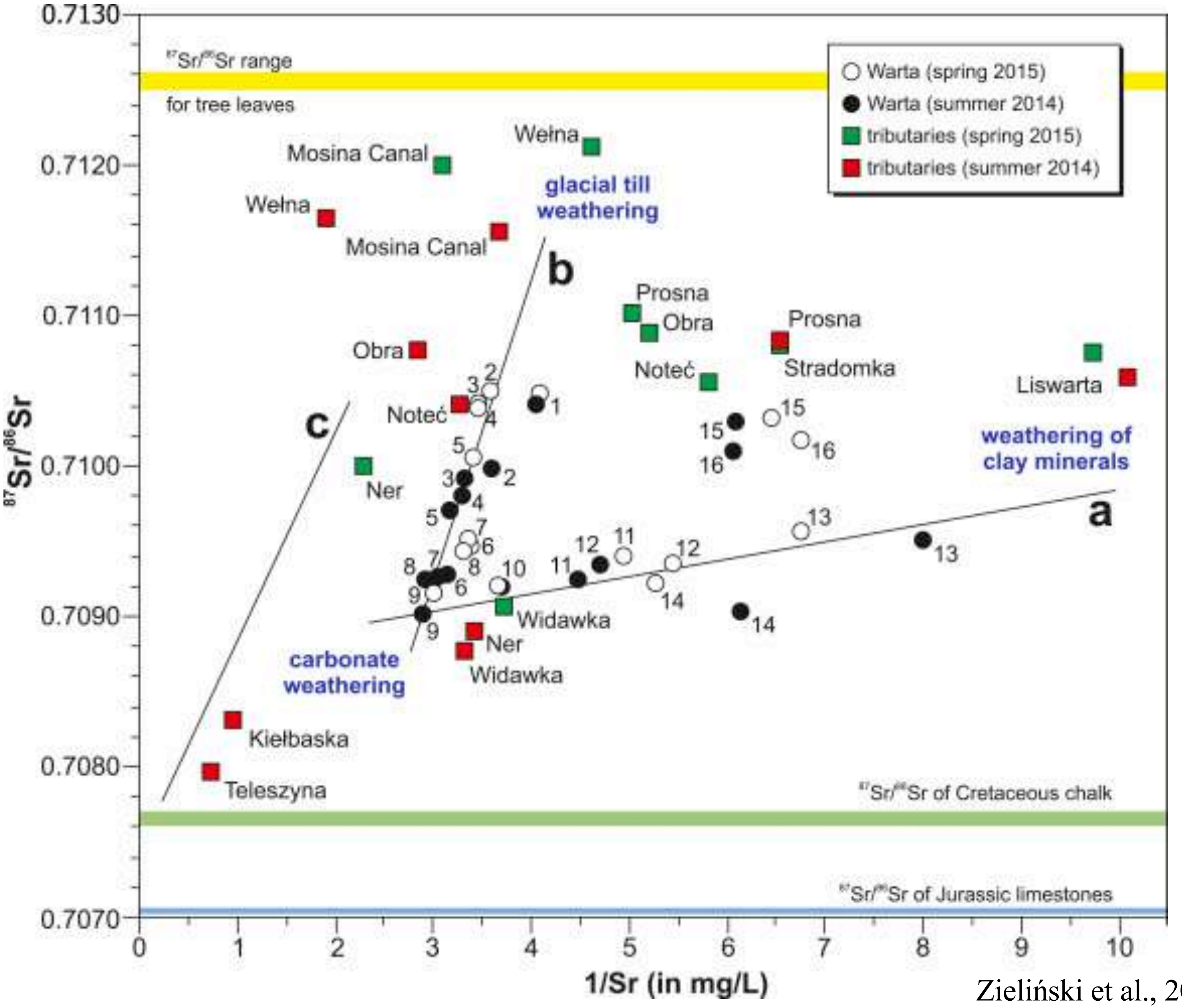
Similarly after time t_2, the ^{87}Rb in the three rocks will again have decayed to ^{87}Sr but a straight line through the points will give the same initial $^{87}Sr/^{86}Sr$ ratio as at time t_0.
time = t_2
time = t_1
time = t_0
C_2
B_2
A_2
C_1
B_1
A_1
$\frac{^{87}Sr}{^{86}Sr}$
Initial ratio $\frac{^{87}Sr}{^{86}Sr}$
Rock A
Rock B
Rock C
$\frac{^{87}Rb}{^{86}Sr}$


One rock with four different minerals each with different Rb/Sr ratios. Also evolve so that they lie along a steeper but still linear line going through the same initial $^{87}Sr/^{86}Sr$ ratio
$\frac{^{87}Sr}{^{86}Sr}$
Initial ratio $\frac{^{87}Sr}{^{86}Sr}$
M_1
M_2
R
M_3
M_4
time = t_1
time = t_0
Min 1
Min 2
Rock
Min 3
Min 4
$\frac{^{87}Rb}{^{86}Sr}$

The initial ratio

- How do we know if a series of sediments are co-genetic?
- For sediments to be co-genetic, implies that they are derived from the same parent material.
- This parent material would have had a single $^{87}Sr/^{86}Sr$ isotope value, ie the initial isotope ratio
- Therefore, all samples derived from the same parent magma should all have the same $^{87}Sr/^{86}Sr$ isotope ratio
- If they don't, it implies that they are derived from a different parent source.


Two suites of samples that are not co-genetic
Rocks A - F have the same age and thus have the same slope. However, they have different initial $^{87}Sr/^{86}Sr$ isotope ratios indicated by the different y-intercepts
time = t_2
C_2
F_2
B_2
E_2
A_2
D_2
$\frac{^{87}Sr}{^{86}Sr}$
Initial ratio rocks A, B, C
Initial ratio rocks D, E, F
A
B
C
D
E
F
time = t_0
time = t_0
$\frac{^{87}Rb}{^{86}Sr}$



Zieliński et al., 2017

Mixing Theory

- Geochemistry often tries to model variations in measured composition as the result of mixing of a small number of *components* [N.B. a different use of component from the thermodynamic usage] or *end members*
  - This reduces highly multivariate data to a few manageable dimensions
  - It allows identification of the end members with particular source or fluxes, hence a meaningful interpretation of data
  - Many geochemical processes are easily understood in terms of mixing or unmixing:
    - river water + ocean water = mixing
    - primary liquid – fractionated crystals = unmixing
- We will work out the mixing relations for several spaces:
  - Element-element plots
  - Element-ratio plots (including elemental and isotope ratios)
  - Ratio-ratio plots

Mixing Theory

- Mixing is simplest to see and understand when there are only two end members: *Binary mixing*
- For concreteness, instead of a bunch of general symbols, let's do all this with two end members, *a* and basalt *b*, with the following compositions:

	a	*b*
[Sr]	100 ppm	400 ppm
[Nd]	2 ppm	20 ppm
$^{87}Sr/^{86}Sr$	0.712	0.704
$^{143}Nd/^{144}Nd$	0.511	0.513

- The same relationships will apply for mixing of major elements as for trace elements.
- The same relationships will apply for ratios of major elements, ratios of trace element concentrations, and ratios of isotopes.

Binary Mixing I: element-element

- This is the simplest case. Binary mixing in concentration-concentration space always generates *lines*.
- Let mixtures be generated with mass fraction f_a of end member a and f_b of end member b, such that $f_a + f_b = 1$.
- Then for two species, say Sr and Nd, we have conservation of atoms and mass in the form

$$[\mathrm{Sr}]_{mix} = f_b[\mathrm{Sr}]_b + (1 - f_b)[\mathrm{Sr}]_a$$
$$[\mathrm{Nd}]_{mix} = f_b[\mathrm{Nd}]_b + (1 - f_b)[\mathrm{Nd}]_a$$

- This can be written

$$[\mathrm{Sr}]_{mix} - [\mathrm{Sr}]_a = f_b([\mathrm{Sr}]_b - [\mathrm{Sr}]_a)$$
$$[\mathrm{Nd}]_{mix} - [\mathrm{Nd}]_a = f_b([\mathrm{Nd}]_b - [\mathrm{Nd}]_a)$$

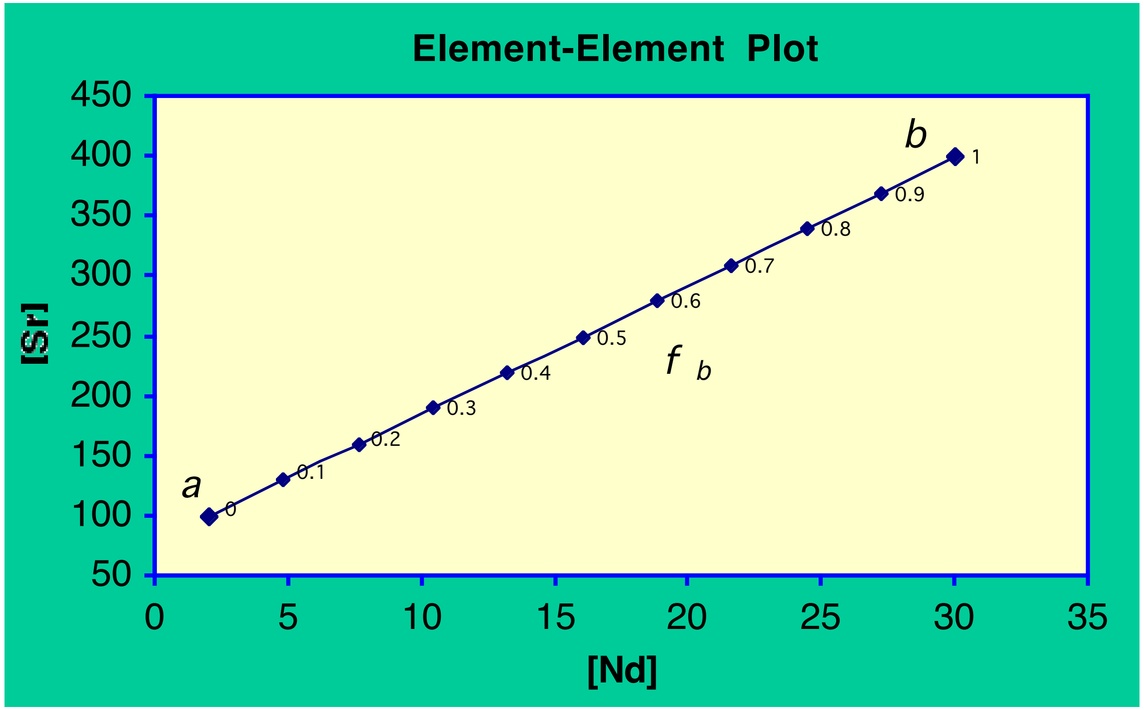
- Dividing these two equations gives the equation of the mixing relationship in ([Sr],[Nd]) space:

$$[Sr]_{mix} - [Sr]_a = \frac{[Sr]_b - [Sr]_a}{[Nd]_b - [Nd]_a}\left([Nd]_{mix} - [Nd]_a\right)$$

Binary Mixing I: element-element

$$[Sr]_{mix} - [Sr]_a = \frac{[Sr]_b - [Sr]_a}{[Nd]_b - [Nd]_a}\left([Nd]_{mix} - [Nd]_a\right)$$

- This is the equation of a *line* with slope $\dfrac{[Sr]_b - [Sr]_a}{[Nd]_b - [Nd]_a}$
- Passing through points $([Nd]_a,[Sr]_a)$ and $([Nd]_b,[Sr]_b)$



Binary Mixing I: element-element

- If you *know* the compositions of the end members, you can solve for f_b using the lever rule:

$$f_b = \frac{[Sr]_{mix} - [Sr]_a}{[Sr]_b - [Sr]_a} = \frac{[Nd]_{mix} - [Nd]_a}{[Nd]_b - [Nd]_a}$$

- If you *don't know* the end members, but only the data, what can you learn from a graph showing a linear correlation?
  - You can infer that if generated by mixing there are only two end members, otherwise the data would fill a triangle
  - You can infer that both end members lie on the mixing line, outside the extreme range of the data on both ends if they must have positive amounts (*additive mixing*)

Binary Mixing II: Ratio

- In geochemistry we very frequently work with ratios, either isotope ratios or ratios of concentrations.
  - Sometimes a ratio is all you can measure accurately
  - Sometimes ratios have significance where concentrations are more or less arbitrary (example: during fractionation of olivine from a basalt, [Sr] will change because it is incompatible and the amount of liquid is decreasing, but [Sr]/[Nd] will not)
- You might think that the $^{87}Sr/^{86}Sr$ ratio of mixtures could be obtained in the same way as for [Sr]

$$(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_{mix} = f_b\,(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_b + (1 - f_b)\,(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_a$$

- You would be wrong!
- The isotope ratio of the mixture is going to be weighted by the concentration of Sr in each end member
  - More generally, the weighting of ratios in the mixture is controlled by the denominator of the ratio, in this case ^{86}Sr.

Binary Mixing II: Ratio

- Let's do it right: we have

$$[{}^{87}\mathrm{Sr}]_{mix} = f_b\,[{}^{87}\mathrm{Sr}]_b + (1 - f_b)\,[{}^{87}\mathrm{Sr}]_a$$

$$[{}^{86}\mathrm{Sr}]_{mix} = f_b\,[{}^{86}\mathrm{Sr}]_b + (1 - f_b)\,[{}^{86}\mathrm{Sr}]_a$$

- Taking the ratio of these, we have

$$\left(\frac{{}^{87}Sr}{{}^{86}Sr}\right)_{mix} = \frac{f_b\left[{}^{87}Sr\right]_b + (1 - f_b)\left[{}^{87}Sr\right]_a}{f_b\left[{}^{86}Sr\right]_b + (1 - f_b)\left[{}^{86}Sr\right]_a}$$

- And substituting $[{}^{87}\mathrm{Sr}] = ({}^{87}\mathrm{Sr}/{}^{86}\mathrm{Sr})[{}^{86}\mathrm{Sr}]$ for *a* and *b*:

$$\left(\frac{{}^{87}Sr}{{}^{86}Sr}\right)_{mix} = \frac{f_b\left[{}^{86}Sr\right]_b\left(\frac{{}^{87}Sr}{{}^{86}Sr}\right)_b + (1 - f_b)\left[{}^{86}Sr\right]_a\left(\frac{{}^{87}Sr}{{}^{86}Sr}\right)_a}{f_b\left[{}^{86}Sr\right]_b + (1 - f_b)\left[{}^{86}Sr\right]_a}$$

- We can approximate this using [Sr] instead of $[{}^{86}\mathrm{Sr}]$ as the weighting factors.

Binary Mixing II: Ratio

- Now let's consider plotting the isotope ratio of the mixture against an elemental concentration, perhaps [Nd].
- If we eliminate f_b between the mixing equation for (^{87}Sr/^{86}Sr) and [Nd], we obtain the following equation (using the approximation Sr ~ ^{86}Sr):

$$A\left(\frac{^{87}Sr}{^{86}Sr}\right)_{mix} + B[Nd]_{mix}\left(\frac{^{87}Sr}{^{86}Sr}\right)_{mix} + C[Nd]_{mix} + D = 0$$

$$A = [Nd]_b[Sr]_a - [Nd]_a[Sr]_b$$

$$B = [Sr]_b - [Sr]_a$$

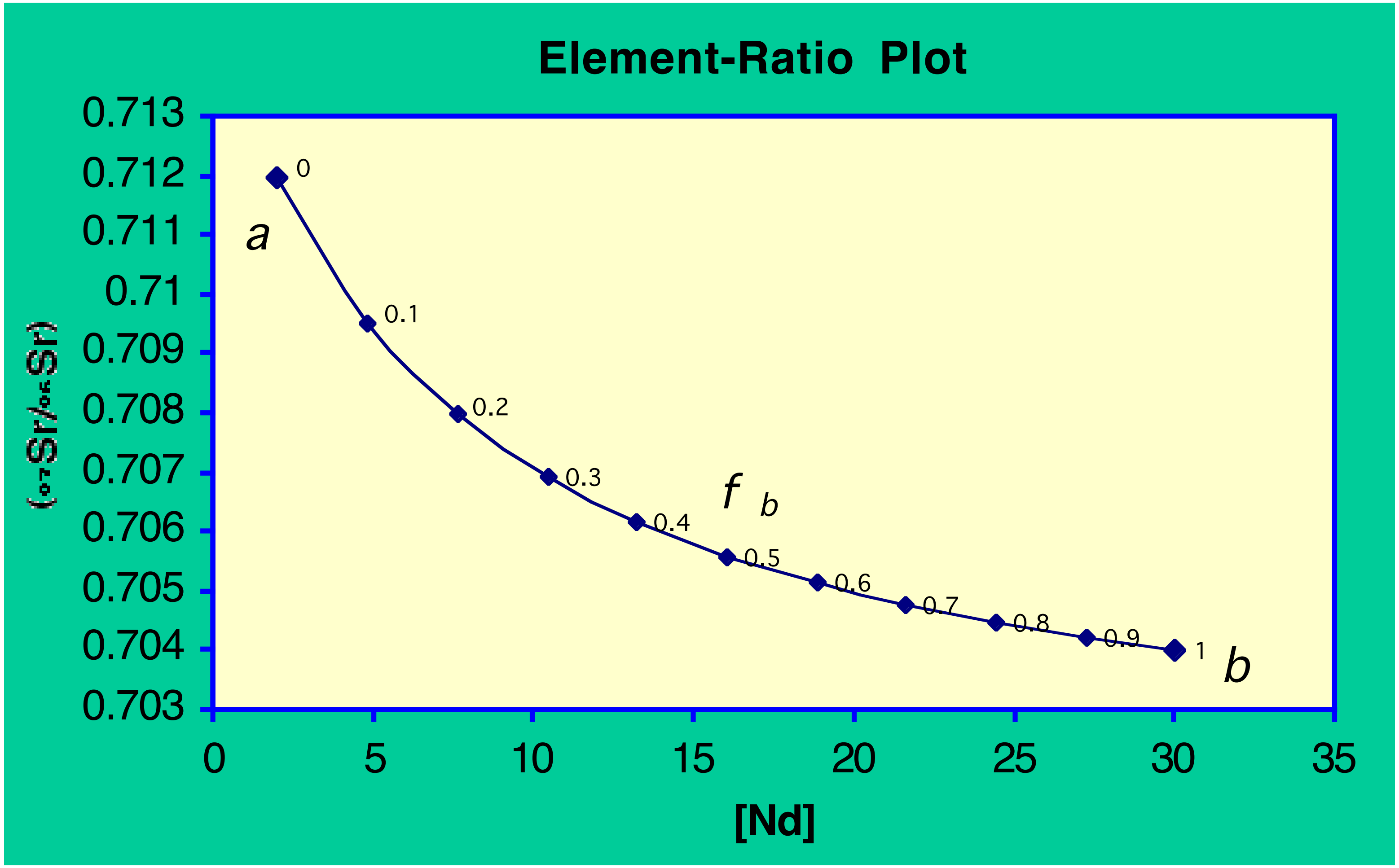
$$C = [Sr]_a\left(\frac{^{87}Sr}{^{86}Sr}\right)_a - [Sr]_b\left(\frac{^{87}Sr}{^{86}Sr}\right)_b$$

$$D = [Nd]_a[Sr]_b\left(\frac{^{87}Sr}{^{86}Sr}\right)_b - [Nd]_b[Sr]_a\left(\frac{^{87}Sr}{^{86}Sr}\right)_a$$

- Equation Ax +Bxy +Cy + D = 0?

Binary Mixing II: element-ratio

- In general, element-ratio mixing generates a *hyperbola*.
  - The only case in which it is linear is $B = [Sr]_b - [Sr]_a = 0$



- The index of curvature $r = [Sr]_b/[Sr]_a$ tells you "how hyperbolic" the hyperbola is going to be.

Binary Mixing III: Inverse Element-Ratio

- Although there is nothing special about the element-ratio case A/B vs. B (thus ($^{87}Sr/^{86}Sr$) vs. [Sr] is still hyperbolic), there is an especially useful test for mixing if you plot A/B vs. 1/B (in this case, ($^{87}Sr/^{86}Sr$) vs. 1/[Sr]).
  - Going back to our hyperbolic equation, if we replace $[Nd]_{mix}$, $[Nd]_a$ and $[Nd]_b$ with $[Sr]_{mix}$, $[Sr]_a$ and $[Sr]_b$ we have:

$$A\left(\frac{^{87}Sr}{^{86}Sr}\right)_{mix} + B[Sr]_{mix}\left(\frac{^{87}Sr}{^{86}Sr}\right)_{mix} + C[Sr]_{mix} + D = 0$$

$$A = [Sr]_b[Sr]_a - [Sr]_a[Sr]_b = 0, B = [Sr]_b - [Sr]_a$$

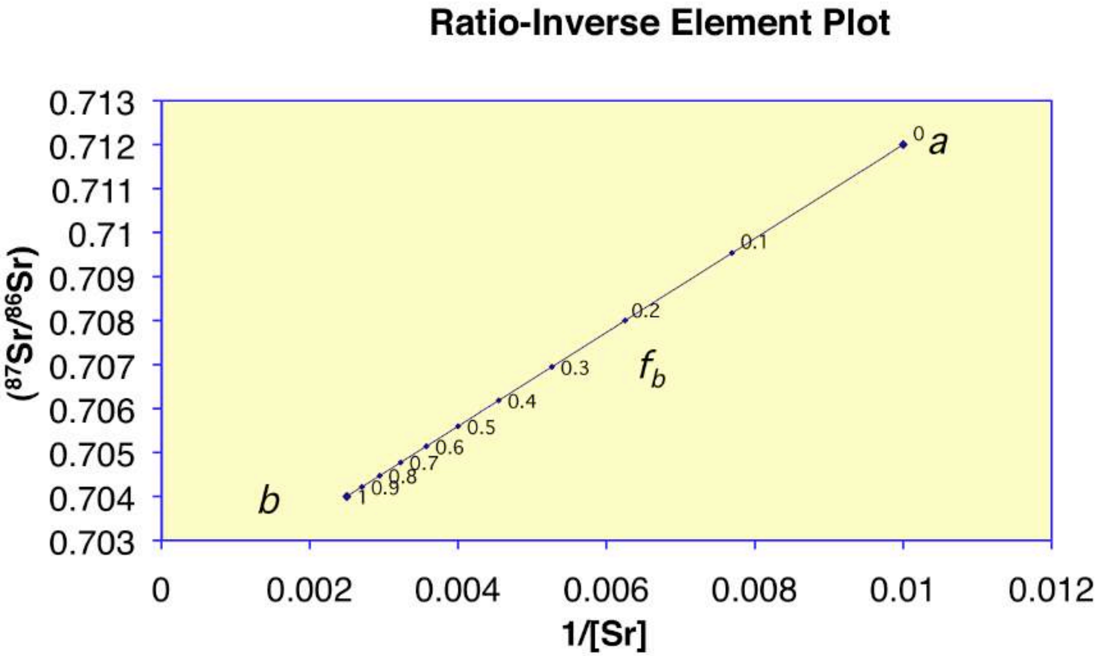
$$C = [Sr]_a\left(\frac{^{87}Sr}{^{86}Sr}\right)_a - [Sr]_b\left(\frac{^{87}Sr}{^{86}Sr}\right)_b$$

$$D = [Sr]_a[Sr]_b\left(\left(\frac{^{87}Sr}{^{86}Sr}\right)_b - \left(\frac{^{87}Sr}{^{86}Sr}\right)_a\right)$$

- Or, $B\left(\frac{^{87}Sr}{^{86}Sr}\right)_{mix} + C + D\frac{1}{[Sr]_{mix}} = 0$, which is a *line*.

Binary Mixing III: inverse element-ratio

- Mixing in A/B vs. 1/B space always generates a line.



- The value of $r = [Sr]_b/[Sr]_a$ now controls how hyperbolic the *spacing* of equal increments of mixing fraction are along the line. Since linear correlation is easy to calculate, it is much easier to test whether data are consistent with binary mixing in this space than in ratio-element space.

Binary Mixing IV: Ratio-Ratio

- Our final case is plots of ratios against ratios, whether isotope ratios, trace element ratios, or major element ratios.
- For example, let's do ($^{87}Sr/^{86}Sr$) vs. ($^{143}Nd/^{144}Nd$).
- We now have two equations of the same form:

$$\left(\frac{^{87}Sr}{^{86}Sr}\right)_{mix} = \frac{f_b[Sr]_b\left(\frac{^{87}Sr}{^{86}Sr}\right)_b + (1-f_b)[Sr]_a\left(\frac{^{87}Sr}{^{86}Sr}\right)_a}{f_b[Sr]_b + (1-f_b)[Sr]_a}$$

$$\left(\frac{^{143}Nd}{^{144}Nd}\right)_{mix} = \frac{f_b[Nd]_b\left(\frac{^{143}Nd}{^{144}Nd}\right)_b + (1-f_b)[Nd]_a\left(\frac{^{143}Nd}{^{144}Nd}\right)_a}{f_b[Nd]_b + (1-f_b)[Nd]_a}$$

Where once again for the particular case of small variations in isotope ratios I have weighted by concentration rather than by the stable denominator isotope.

Binary Mixing IV: ratio-ratio

- This time eliminating f_b between the mixing equations gives

$$A\left(\frac{^{87}Sr}{^{86}Sr}\right)_{mix} + B\left(\frac{^{87}Sr}{^{86}Sr}\right)_{mix}\left(\frac{^{143}Nd}{^{144}Nd}\right)_{mix} + C\left(\frac{^{143}Nd}{^{144}Nd}\right)_{mix} + D = 0$$

$$A = [Nd]_b[Sr]_a\left(\frac{^{143}Nd}{^{144}Nd}\right)_b - [Nd]_a[Sr]_b\left(\frac{^{143}Nd}{^{144}Nd}\right)_a$$

$$B = [Nd]_a[Sr]_b - [Nd]_b[Sr]_a$$

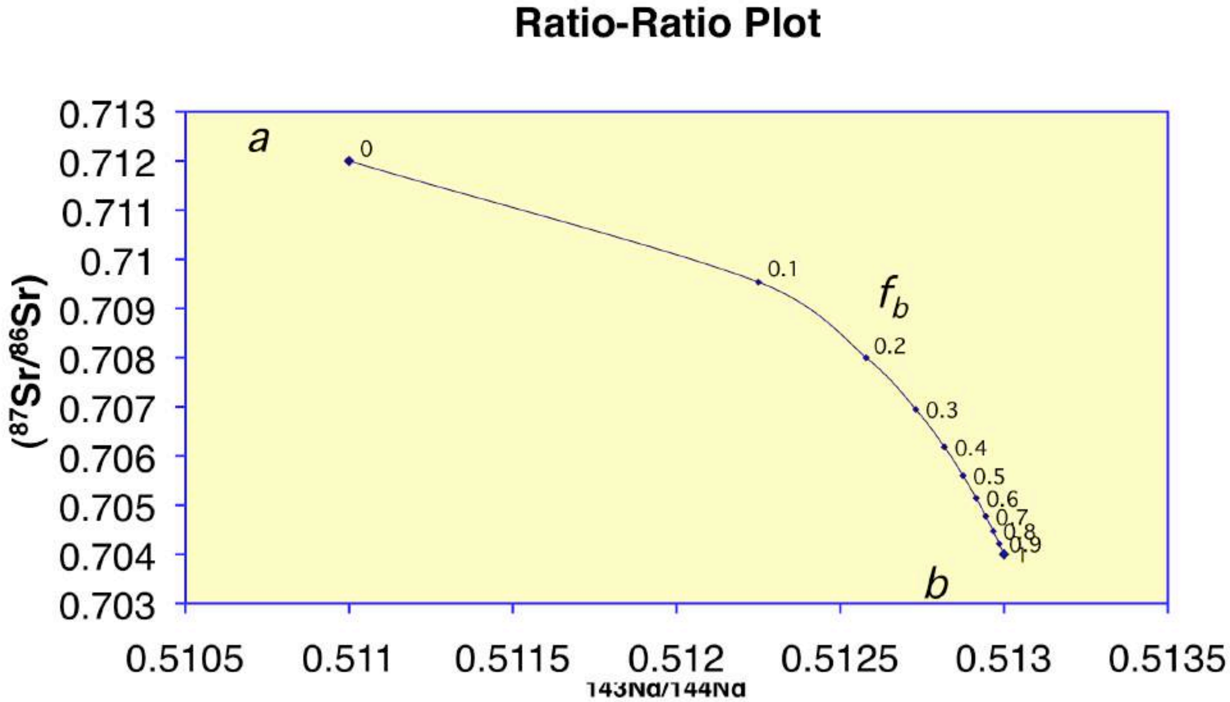
$$C = [Nd]_b[Sr]_a\left(\frac{^{87}Sr}{^{86}Sr}\right)_a - [Nd]_a[Sr]_b\left(\frac{^{87}Sr}{^{86}Sr}\right)_b$$

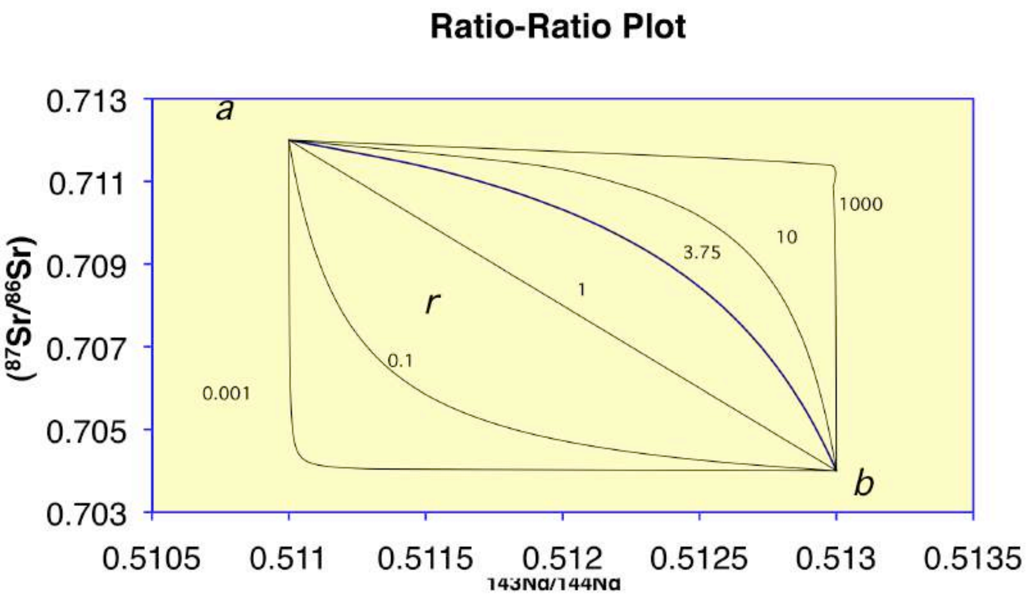
$$D = [Nd]_a[Sr]_b\left(\frac{^{143}Nd}{^{144}Nd}\right)_a\left(\frac{^{87}Sr}{^{86}Sr}\right)_b - [Nd]_b[Sr]_a\left(\frac{^{143}Nd}{^{144}Nd}\right)_b\left(\frac{^{87}Sr}{^{86}Sr}\right)_a$$

- Still a hyperbola. Now term B gives the curvature index
- $r = ([Sr]_a/[Sr]_b)/([Nd]_a/[Nd]_b)$

Binary Mixing IV: ratio-ratio

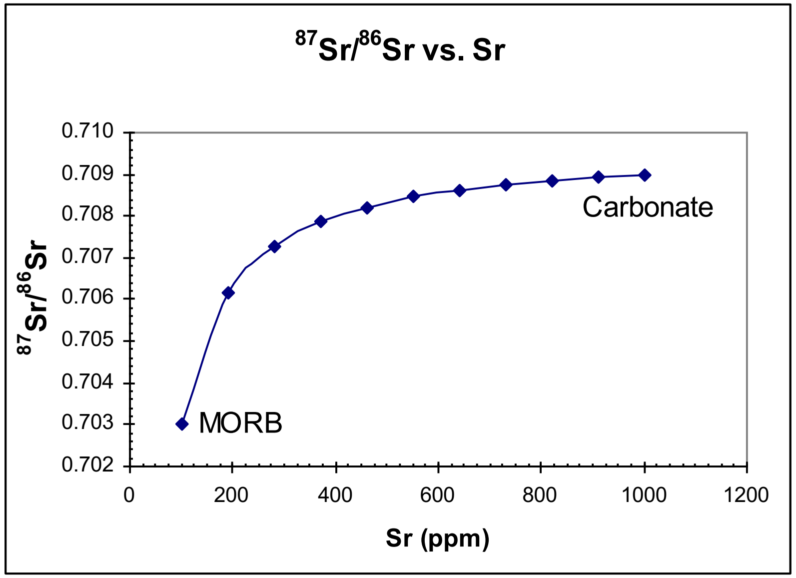
This looks different from the element-ratio hyperbola because now the *spacing* of equal increments of mixing fraction is no longer regular.

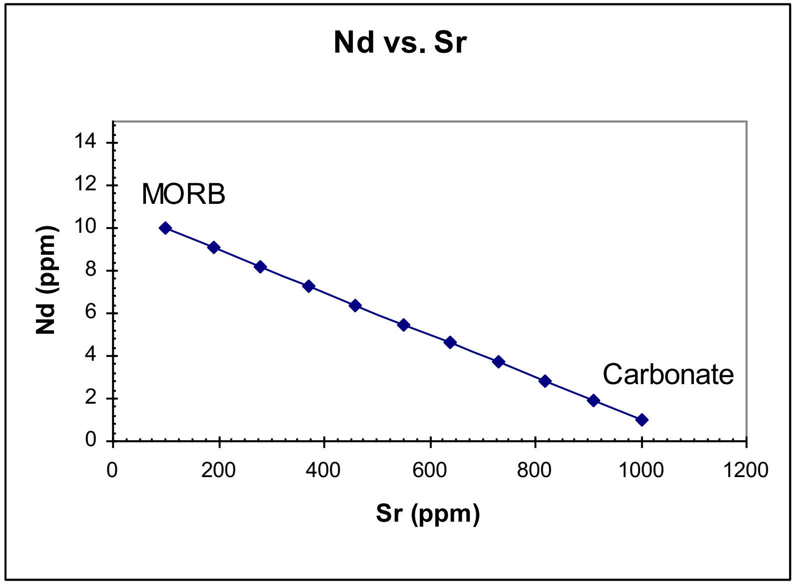


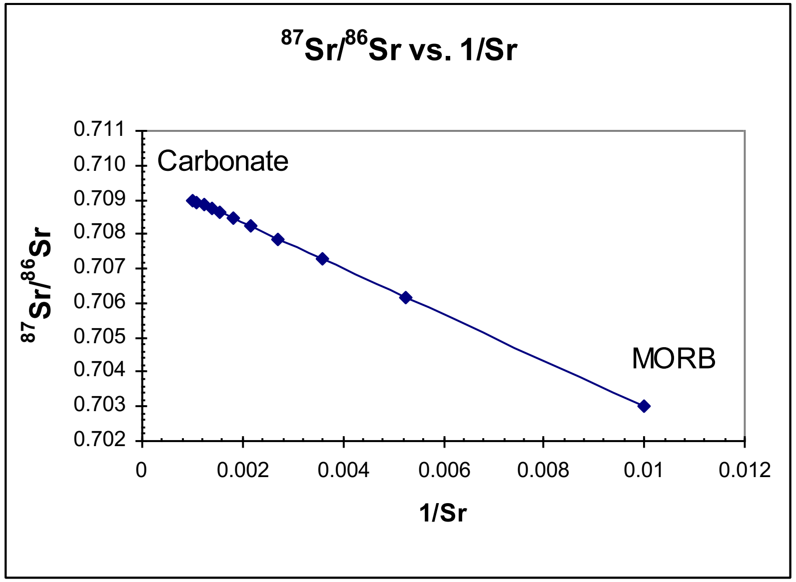


Given an array of ratio-ratio data, you can constrain the curvature parameter as well as the isotope ratios of the end members.

Some mixing plots

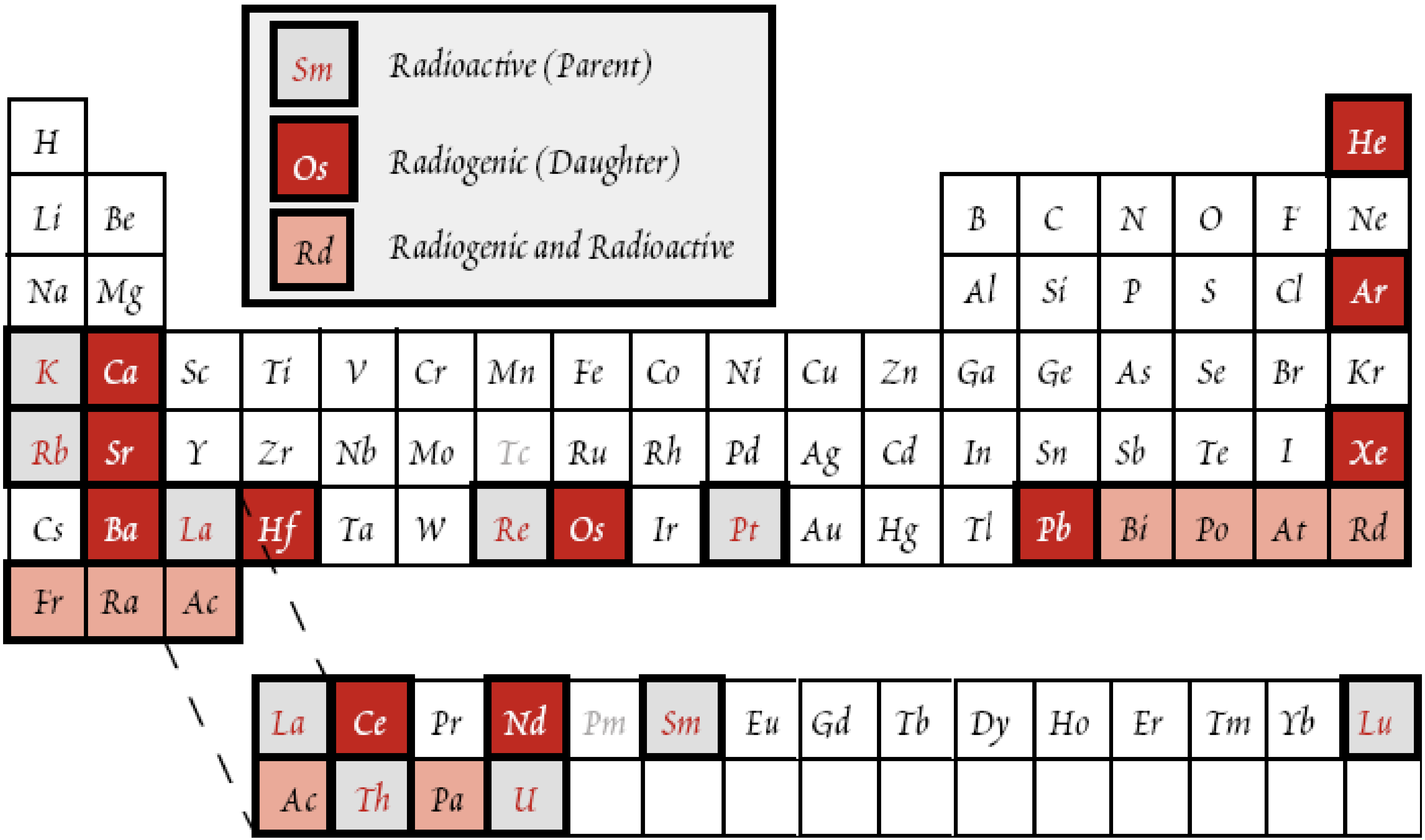






RADIOACTIVE DECAY

Radioactive Isotopes



- **two extremely interesting and important aspects of radioactive decay makes it so useful as a chronometer.**
  - Unstable nuclei decay to stable ones at **rates independent of all environmental influences**.
  - Each nucleus has a **fixed probability of decaying** per unit time. Nothing affects this probability (e.g., temperature, pressure, bonding environment, etc.)

Radiogenic Isotopic variations is a function of:

1. Time (of decay since the system is closed)

2. Different parent/Daughters ratio

Radioactive Decay

- **Basic equation of radioactive decay: first-order rate law: Curie-Rutherford-Soddy Law:**

$$-\frac{dN}{dt} \propto N \quad \text{or} \quad -\frac{dN}{dt} = \lambda N$$ = **Activity of radionuclide**

The minus sign simply indicates N (present-day parent concentration) decreases.

λ **is the decay constant- probability of decay per unit time . Unit: time^{-1}.**

- Integrating the decay equation, we get:

$$N = N_0 e^{-\lambda t}$$

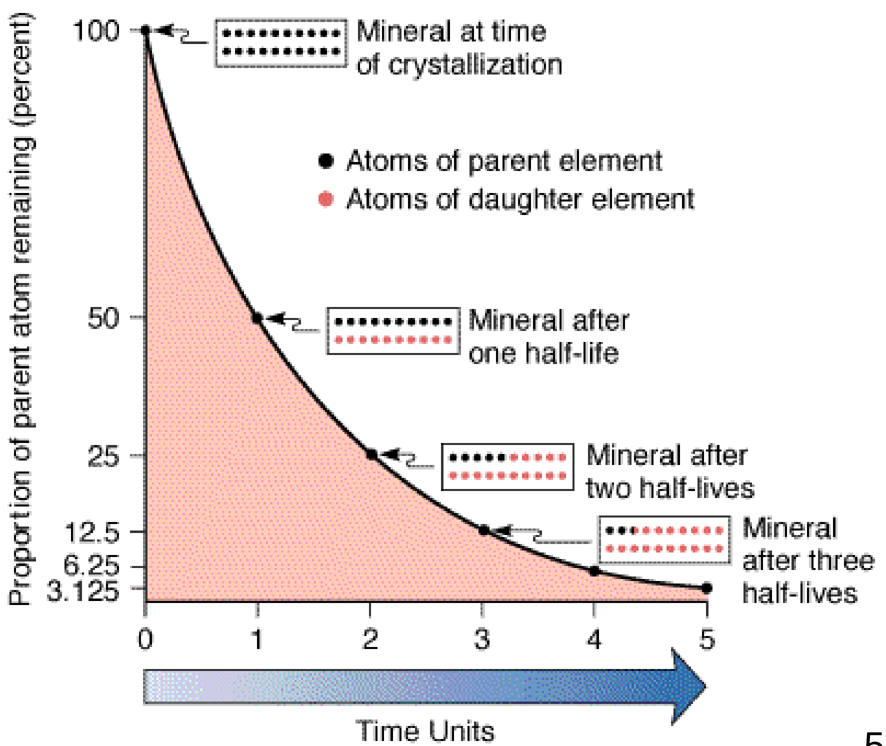
Half-life: $$t_{1/2} = \frac{Ln2}{\lambda} = \frac{0.693}{\lambda}$$

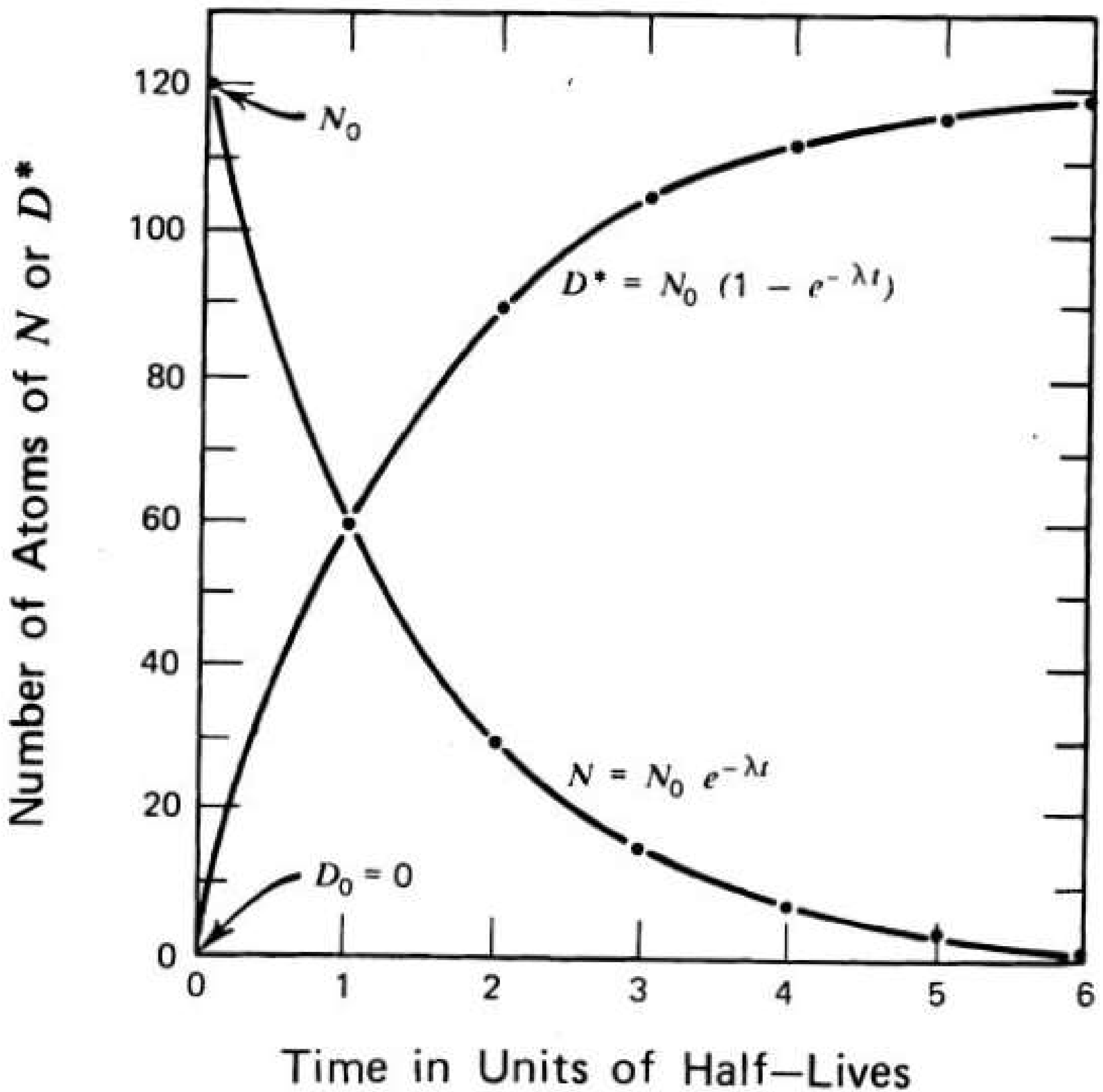
The **mean life** τ of a parent nuclide:

(average life expectancy of a radioactive atom)

$$t\tau = -\frac{1}{N_0}\int_{t=0}^{t=\infty} t\,.\,dN$$

$$\tau = \frac{N}{\lambda N} = \frac{1}{\lambda}$$





120
100
80
60
40
20
0
0
1
2
3
4
5
6
N_0
$D^* = N_0\ (1 - e^{-\lambda t})$
$N = N_0\ e^{-\lambda t}$
$D_0 = 0$
Number of Atoms of N or D^*
Time in Units of Half–Lives

The decay of the parent produces a daughter (D^*), or radiogenic nuclide.

$$D^* = N_o - N$$

$$= Ne^{\lambda t} - N \quad = N\,(e^{\lambda t} - 1)$$

- **However, there might be some daughter isotope present in the system (initial value) to begin with.**

Therefore: $D = D_o + D^*$

$$\boxed{D = D_o + N(e^{\lambda t}-1)}$$

D = number of daughter atoms

N = number of existing parent atoms

D_o = number of initial daughter atoms

λ = decay constant

t = time elapsed

$$\boxed{D = D_o + N(e^{\lambda t}-1)}$$

Note that this equation is independent of N_0.

solve the above equation for age of the system (t):

$$t = \frac{1}{\lambda} \mathrm{Ln} \left[\frac{D - D_0}{N} + 1\right]$$

Practical limitations on age range:

Very young rocks: cannot measure tiny amount of daughter accurately

Very old rocks: cannot measure tiny amounts of parent left accurately

Applicability of an Isotopic system depends on λ.

Geologically Useful Long-Lived Radioactive Decay Schemes

TABLE 2.1: Geologically Useful Long-Lived Radioactive Decay Schemes

Parent	Decay Mode	λ	Half-life	Daughter	Ratio
^{40}K	β^-, e.c, β^+	$5.5492 \times 10^{-10} y^{-1*}$	1.28×10^9 yr	^{40}Ar, ^{40}Ca	$^{40}Ar/^{36}Ar$
^{87}Rb	β^-	$1.42 \times 10^{-11} y^{-1£}$	48.8×10^9 yr	^{87}Sr	$^{87}Sr/^{86}Sr$
^{138}La	β^-	$2.67 \times 10^{-12} y^{-1}$	2.59×10^{11} yr	^{138}Ce, ^{138}Ba	$^{138}Ce/^{142}Ce$, $^{138}Ce/^{136}Ce$
^{147}Sm	α	$6.54 \times 10^{-12} y^{-1}$	1.06×10^{11} yr	^{143}Nd	$^{143}Nd/^{144}Nd$
^{176}Lu	β^-	$1.867^{\dagger} \times 10^{-11} y^{-1}$	3.6×10^{10} yr	^{176}Hf	$^{176}Hf/^{177}Hf$
^{187}Re	β^-	$1.64 \times 10^{-11} y^{-1}$	4.23×10^{10} yr	^{187}Os	$^{187}Os/^{188}Os$, ($^{187}Os/^{186}Os$)
^{190}Pt	α	$1.54 \times 10^{-12} y^{-1}$	4.50×10^{11} yr	^{186}Os	$^{186}Os/^{188}Os$
^{232}Th	α	$4.948 \times 10^{-11} y^{-1}$	1.4×10^{10} yr	^{208}Pb, ^{4}He	$^{208}Pb/^{204}Pb$, $^{3}He/^{4}He$
^{235}U	α	$9.8571 \times 10^{-10} y^{-1\ddagger}$	7.07×10^8 yr	^{207}Pb, ^{4}He	$^{207}Pb/^{204}Pb$, $^{3}He/^{4}He$
^{238}U	α	$1.55125 \times 10^{-10} y^{-1}$	4.47×10^9 yr	^{206}Pb, ^{4}He	$^{206}Pb/^{204}Pb$, $^{3}He/^{4}He$

Note: the branching ratio, i.e. ratios of decays to ^{40}Ar to total decays of ^{40}K is 0.117. ^{147}Sm and ^{190}Pt also produce ^{4}He, but a trivial amount compared to U and Th.

*This is the value recently suggested by Renne et al. (2010). The conventional value is $5.543 \times 10^{-10} y^{-1}$

£The officially accepted decay constant for ^{87}Rb is that shown here. However, recent determinations of this constant range from $1.421 \times 10^{-11} y^{-1}$ by Rotenberg (2005) to $1.399 \times 10^{-11} y^{-1}$ by Nebel et al. (2006).

†This is the value recommended by Söderlund et al. (2004).

‡Value suggested by Mattinson (2010). The conventional value is $9.8485 \times 10^{-10} y^{-1}$.

Isochron Dating

$$^{87}Rb_{37} \rightarrow {}^{87}Sr_{38} + \beta^{-} + \nu + 0.275 \text{ Mev}$$

(λ = 1.42 x 10^{-11} yr^{-1} ; $T_{1/2}$ = 48.8 Ga)

$$^{87}Sr = {}^{87}Sr_0 + {}^{87}Rb\left(e^{\lambda t} - 1\right)$$

As it turns out, it is generally much easier, and usually more meaningful, to measure ratio of two isotopes precisely than the absolute abundance of one. We, therefore, measure the ratio of ^{87}Sr to a non-radiogenic isotope, which by convention is ^{86}Sr. We can recast the above equation as:

$$\frac{^{87}Sr}{^{86}Sr} = \left(\frac{^{87}Sr}{^{86}Sr}\right)_0 + \frac{^{87}Rb}{^{86}Sr}\left(e^{\lambda t} - 1\right)$$

Measured for today

Estimated from isochrons

Measured for today

Assumptions in age determination

1) **System was closed between $t = 0$ and time t (usually the present time)**

   -no transfer of the parent or the daughter element into or out of the system

2) **At $t = 0$, Concentration of parent must be different in different phases in the system, but concentration of initial daughter must be the same.**

3) **we must also know λ accurately**

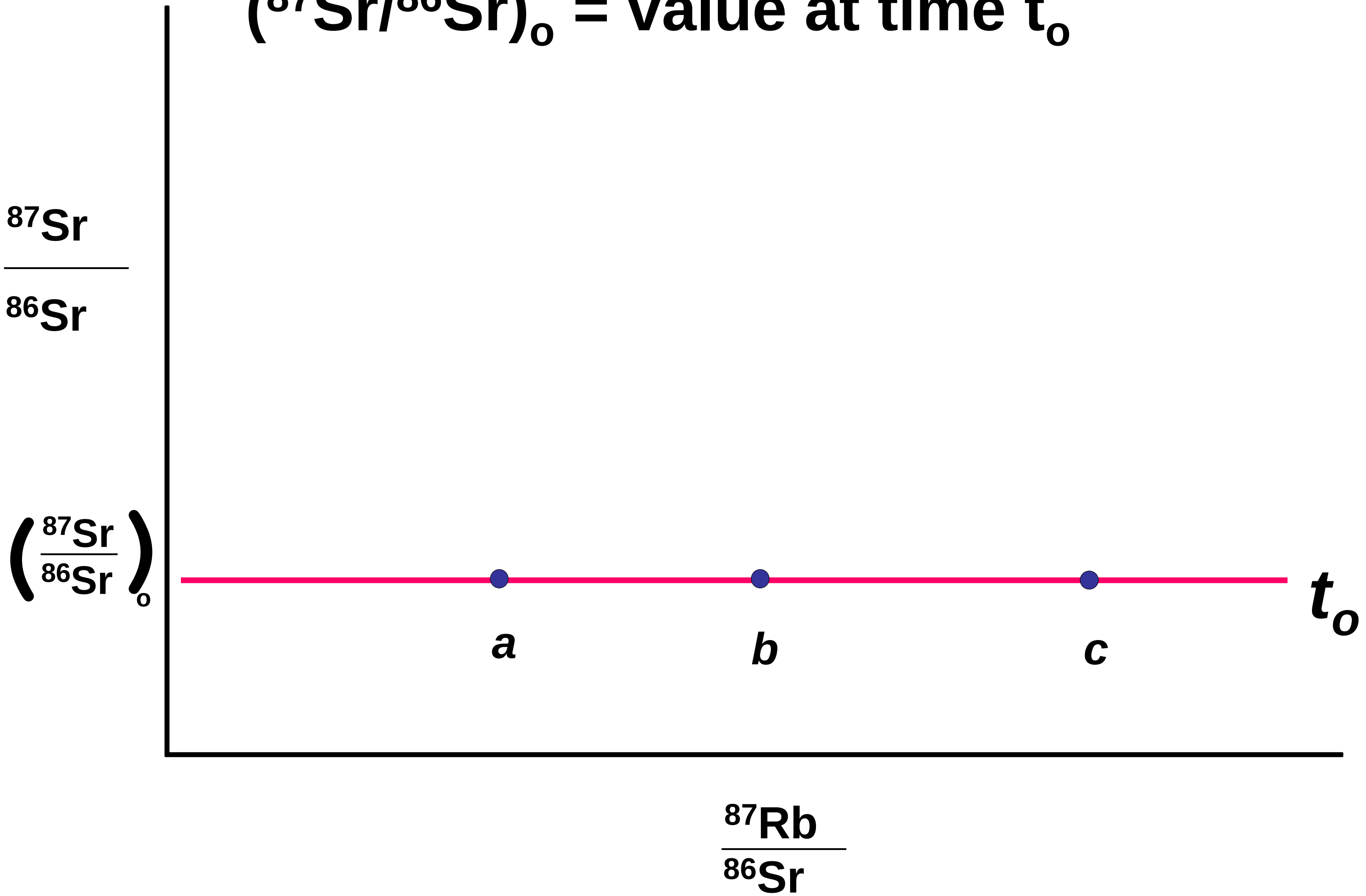
Violation of these conditions is the principal source of error in geochronology. Other errors arise from errors or uncertainties associated with the analysis.

Must satisfy: System is closed

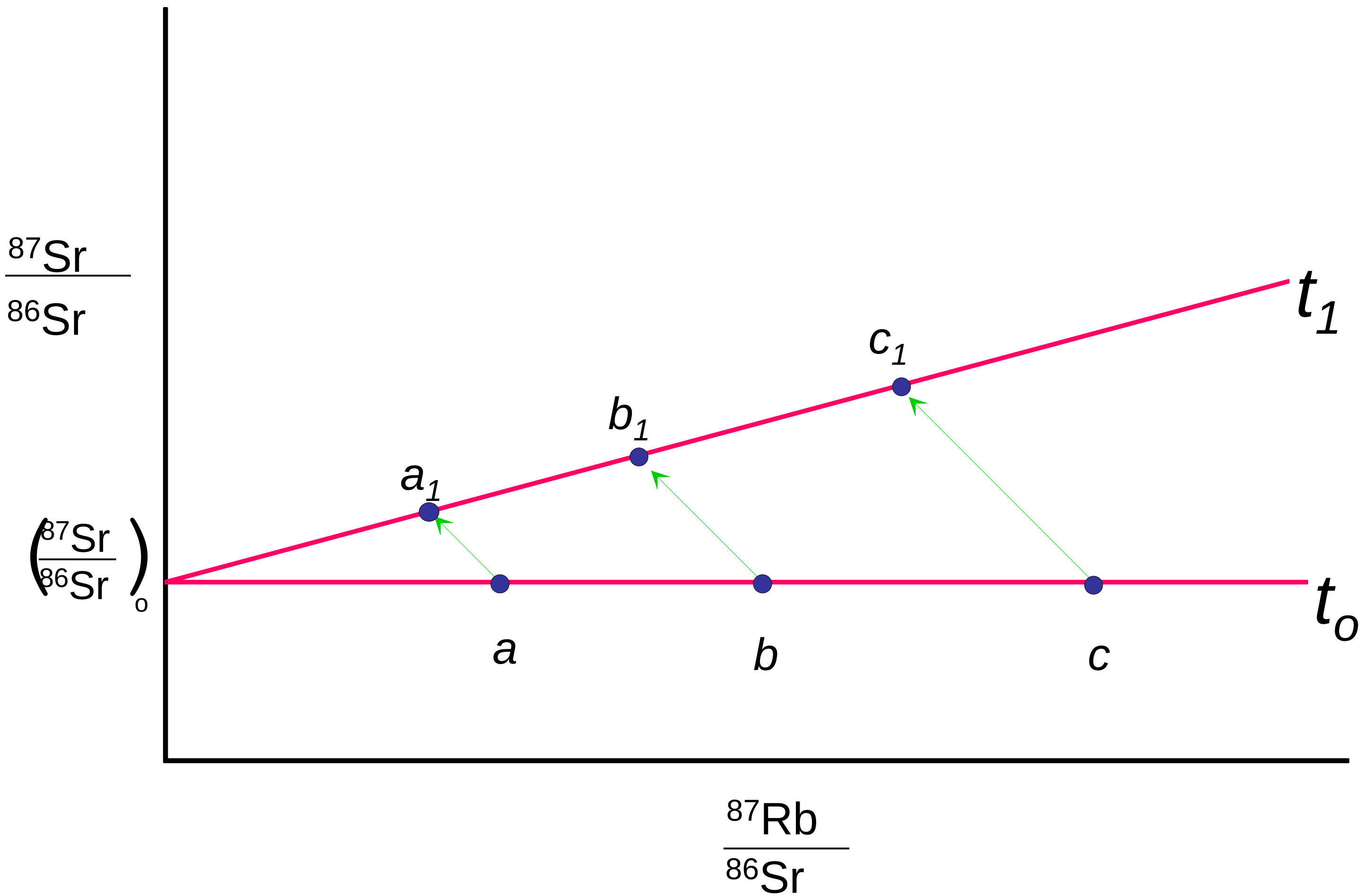
Begin with 3 rocks plotting at a, b, c at time t_o

They must have same value of initial $^{87}Sr/^{86}Sr$

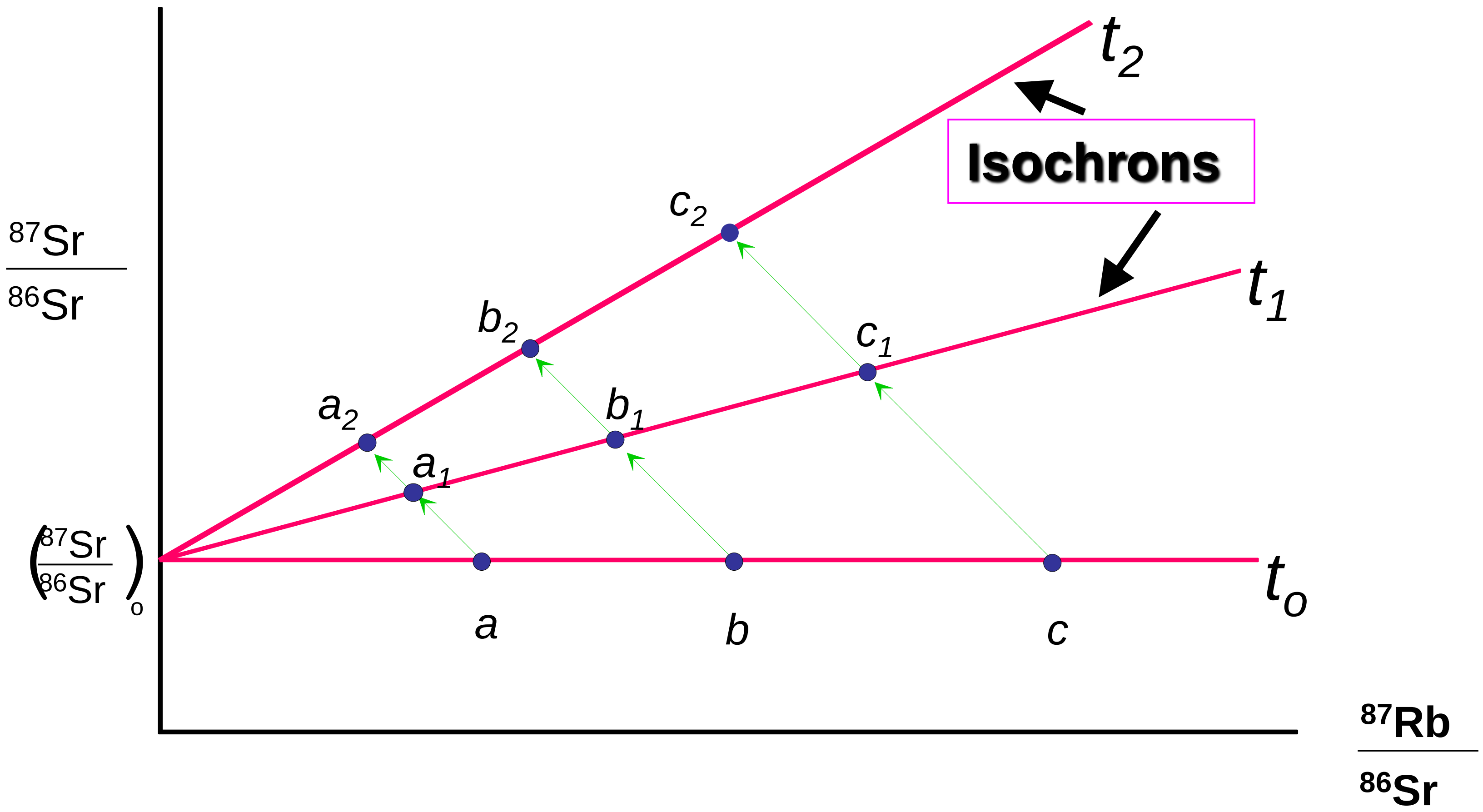
$(^{87}Sr/^{86}Sr)_o$ = value at time t_o



After some time increment ($t_0 \rightarrow t_1$) each sample loses some ^{87}Rb and gains an equivalent amount of ^{87}Sr (proportional to the amount of Rb present in the system)



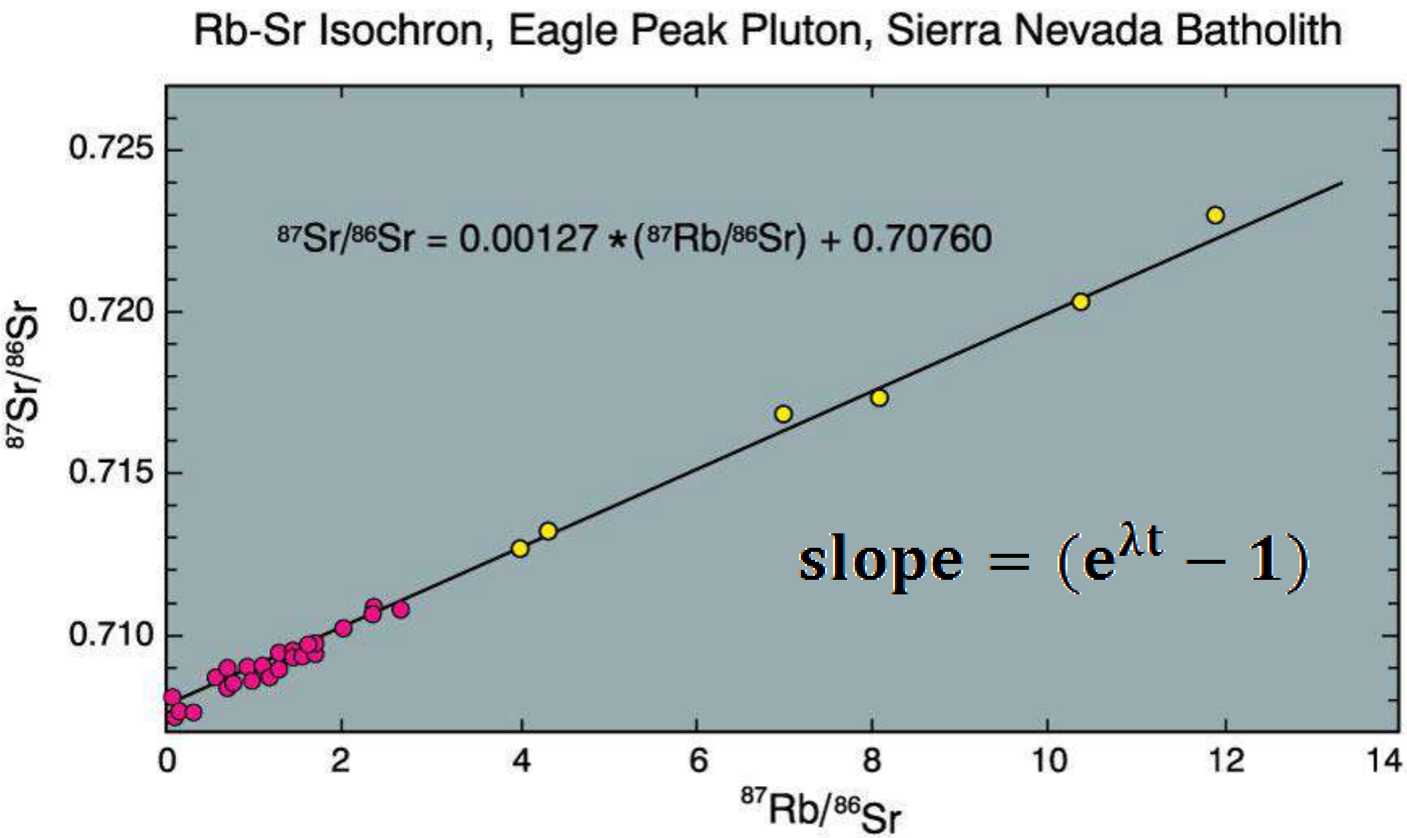
At time t_2 each rock system has evolved $\rightarrow$ new line. Again still linear and steeper line



All points on a single isochron line have same age.

Isochron technique produces 2 valuable things:

1. The **age** of the rocks (from the slope)
2. $(^{87}Sr/^{86}Sr)_o$ = the initial value of $^{87}Sr/^{86}Sr$, which we did not know beforehand



Rb-Sr isochron for the Eagle Peak Pluton, central Sierra Nevada Batholith, California, USA. Filled circles are whole-rock analyses, open circles are hornblende separates. The regression equation for the data is also given. After Hill et al. (1988). Amer. J. Sci., 288-A, 213-241.

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 29. Layered Earth

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Earth's interior
- Different layers and their properties

Reading:
- Marshak's Book (Chapter 2)
- Grotinger & Jordan's book (Chapter 14)
  [*for the entire week*]

Surface of the Earth

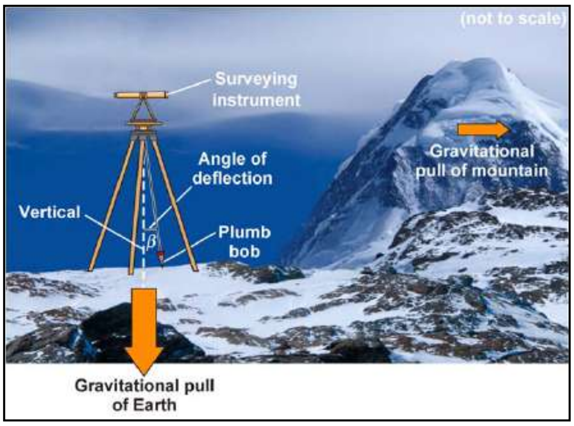
- Our experience with Earth is limited to its surface.
- Dramatic elevation changes—mountains, canyons—are tiny “scratches” on this surface.
- Our Earth is much more vast and complex than the surface suggests.

The Layered Earth

- How do we know that the Earth has a layered interior?
- Early speculations sought to explain:
  - The source of lava.
  - Gem and mineral enrichment.
  - Earthquakes.
- Early guesses were wrong.
  - Open caverns to the interior
  - Flowing lava, air, water

The Layered Earth

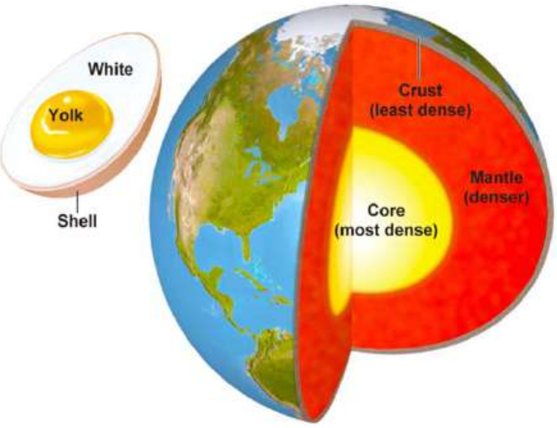
- The first key to understanding Earth's interior: density.
  - A plumb bob is deflected by a nearby mountain mass.
  - Degree of deflection can be used to calculate Earth's mass.
  - The density from this method (4.5 g/cm^3) is much higher than the density of the thin outer crust (2.5 g/cm^3).
  - This suggests that density must increase with depth.



Watch "**Schiehallion experiment**" here: https://vimeo.com/16031284

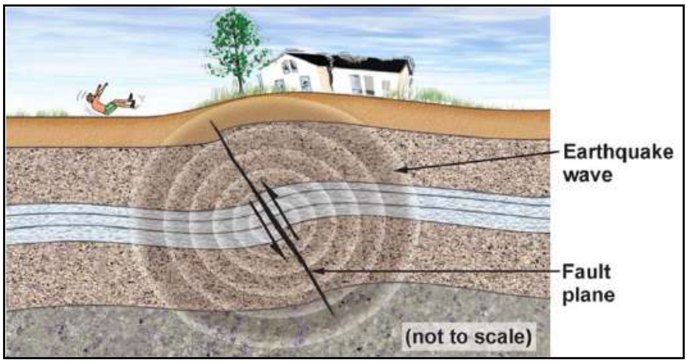
The Layered Earth

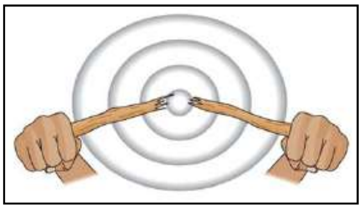
- The first key to understanding Earth's interior: **density.**
  - In 1896, Emil Wiechert made important contributions.
    - He determined that metal must be present in Earth's center
  - We now know he was correct.
  - His ideas led to a model:
    - Earth is like an egg.
      - Thin, light crust (eggshell)
      - Thicker, more dense mantle (eggwhite)
      - Innermost, very dense core (yolk)
  - Other density observations:
    - The land doesn't have large tides, hence Earth's center must be solid.



The Layered Earth

- Earthquakes: seismic energy from fault motion.
  - Seismic waves provide insight into Earth's interior.
    - Seismic wave velocities change with density.
    - We can determine the depth of seismic velocity changes.
    - Hence, we can tell where densities change in Earth's interior.



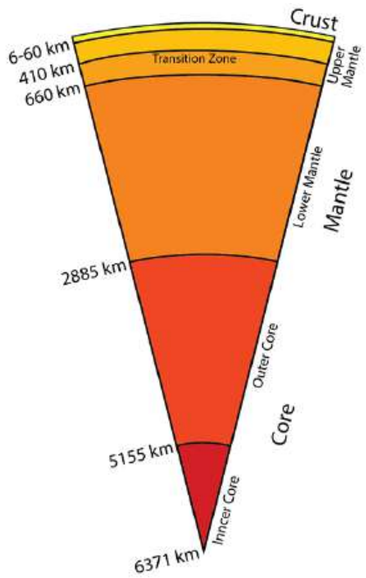


The Layered Earth

- Geologists strived to understand the nature of the layers.
  - Studied meteorites as analogues for core and mantle.
  - Conducted laboratory experiments.
    - Density measurements of rocks from the interior
    - Characteristics of mantle-derived rocks and minerals
    - Determined high P and T stability field of rocks and minerals

The Layered Earth

- End result of a century of investigation?
  - We know much about the nature of Earth's interior.
  - This knowledge continues to evolve.
- Earth's layers consist of the crust, upper, transitional, and lower mantles, and liquid outer and solid inner cores.
- Much complexity characterizes even within these layers.



The Layered Earth

- What are the boundaries?

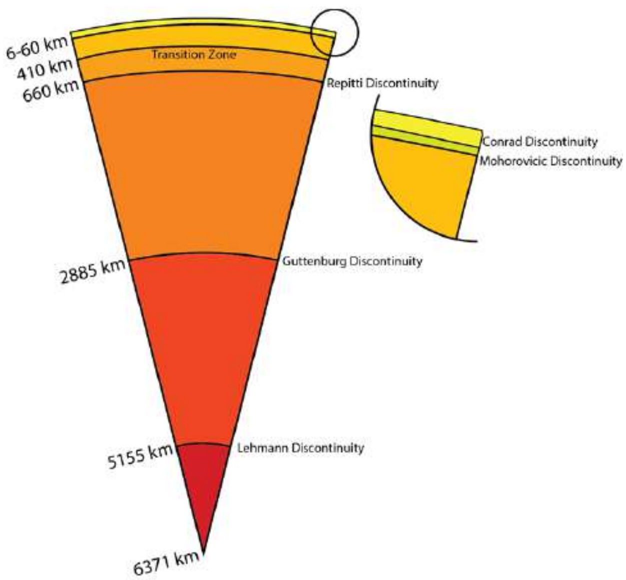
CONRAD discontinuity (15-20 km, for CC only):
between upper and lower Crust (questionable)

MOHOROVICIC discontinuity (6-60 km):
between Crust and Mantle

REPITTI discontinuity (660 km):
between upper and lower Mantle

GUTTENBURG discontinuity (2885 km):
between Mantle and Core

LEHMANN discontinuity (5155 km):
between Outer and Inner Core



The Layered Earth

- How are the layers detected?

The velocity of waves, in general, is a function of the medium they are travelling through

The waves also reflect, and refract at the interfaces of different media

Geologists use all such wave properties, applicable to SEISMIC waves, together with a few more.

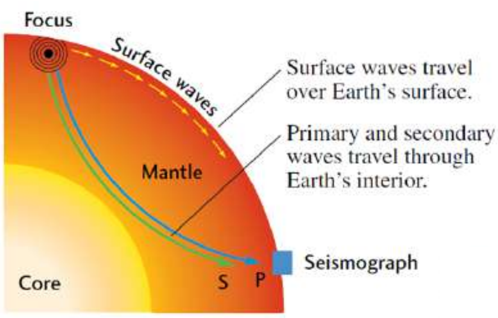
High Density → higher velocity
More solid like → higher velocity

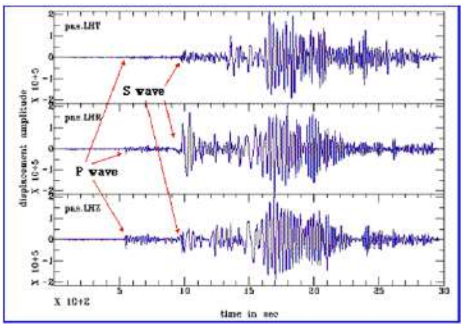
two beams of laser light enter a bowl of water from the top at slightly different angles. Both beams are reflected from a mirror on the bottom of the bowl. One is then reflected at the water-air boundary and passes through the bowl to make a bright spot on the table. Most of the light in the other beam is bent (refracted) as it passes from the water to the air, although a small amount is reflected to form a second spot on the table

The Seismic Waves

Seismic waves (*elastic waves*) are the waves of energy caused by the sudden breaking of rock within the earth or an explosion. They are the energy that travels through the earth and is recorded on seismographs.

The first waves to arrive are called primary waves, or **P waves.** The secondary waves, or **S waves,** follow. Both P waves and S waves travel through Earth's interior and known as **BODY WAVES**. Afterwards come the slower **SURFACE WAVES,** which travel around Earth's surface.



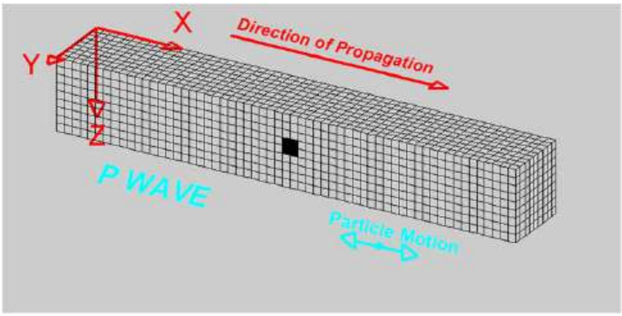


The Seismic Waves

P waves in rock are similar to sound waves in air, except that P waves travel through the solid rock of Earth's crust at about 6 km/s, which is about 20 times faster than sound waves travel through air. Like sound waves, P waves are *compressional waves,* because they travel through solid, liquid, or gaseous materials as a succession of compressions and expansions.

P waves are harmless in terms of earthquake damage.

$$V_P = \sqrt{\frac{K + \left(\frac{4}{3}\right)\mu}{\rho}}$$



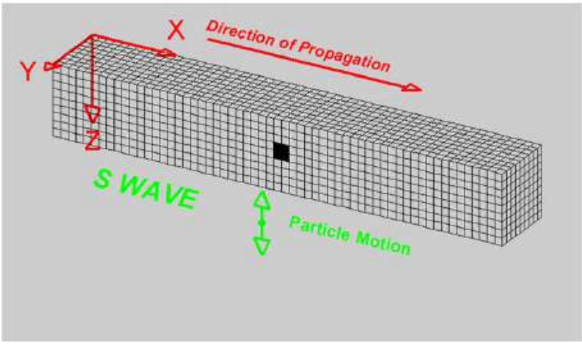
https://www.zmescience.com

The Seismic Waves

S waves (shear waves) travel through solid rock at a little more than half the velocity of P waves. They are *shear waves* that displace material at right angles to their path of travel.

Shear waves cannot travel through liquids or gases and also rarely do any significant damage

$$V_S = \sqrt{\frac{\mu}{\rho}}$$



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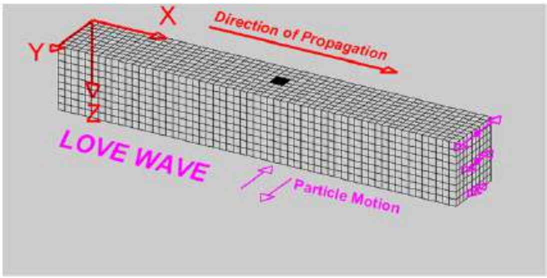
The Seismic Waves

Surface waves **(Love waves)** have a transversal (perpendicular) movement and are the most destructive outside the immediate area of the epicentre. Love waves can be devastating.

Surface waves (Rayleigh waves) do by far the most damage. As opposed to S and P, they propagate on the surface and carry the vast majority of the energy felt on the surface.



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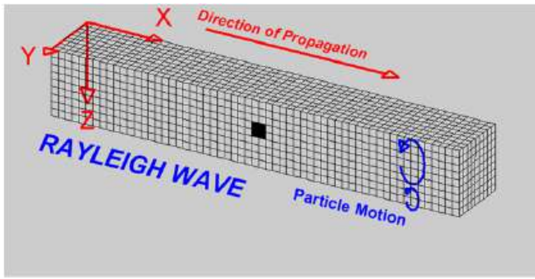

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The Seismic Waves

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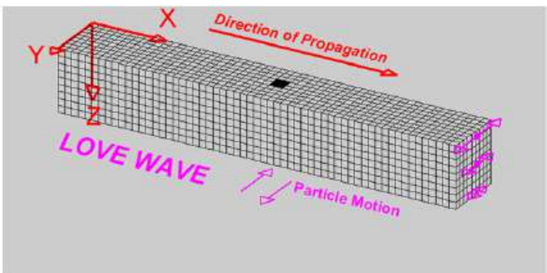

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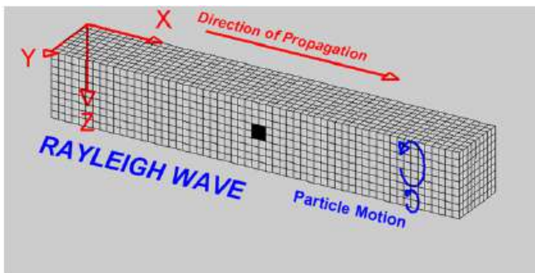
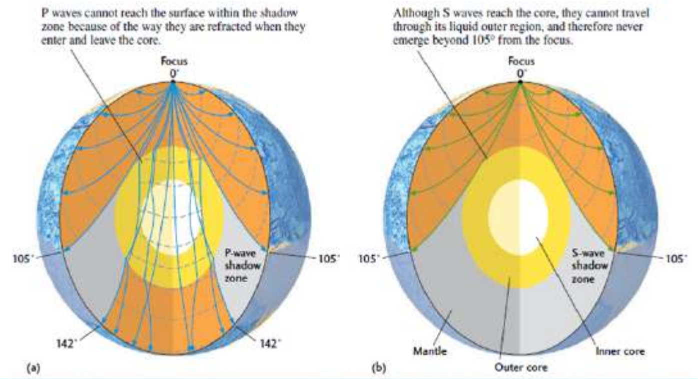


https://www.zmescience.com

Seismic Waves through Earth's interior

Observations of travel times and the amount of upward refraction of the ray paths, suggest that P waves travel much faster through deep Earth than at Earth's surface → THIS IS OKAY.

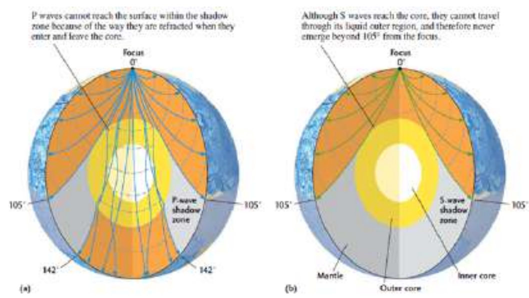
Interestingly, the P and S waves disappear beyond about 11,600 km (105°) from the source [each degree measures 111 km at the surface). Beyond about 15,800 km from the focus (142°), the P waves suddenly reappeared, although they were much delayed compared with their expected travel times. The S waves never reappeared.→ WOW



Seismic Waves through Earth's interior

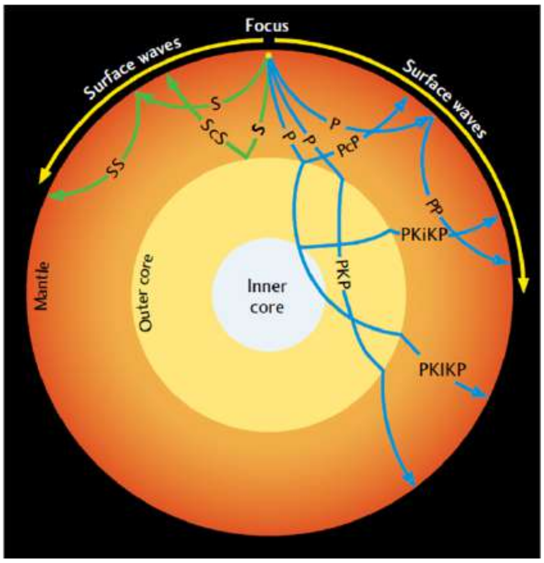
P waves missing from 105-142°: At 105°, ray paths of P waves encounter the core-mantle boundary. At that boundary, P-wave velocity drops by almost a factor of two because of density contrast. The waves are refracted downward into the core and emerge at greater angular distances after the delay caused by their detour through the core.

S waves missing after 105°: Earth a liquid outer core (R. D. Oldham, 1906). S waves cannot travel through the outer core, because it is liquid, and liquids have no resistance to shearing. Thus, there is an S-wave **shadow zone** beyond 105 from the earthquake focus, where S-wave ray paths encounter the core-mantle boundary.



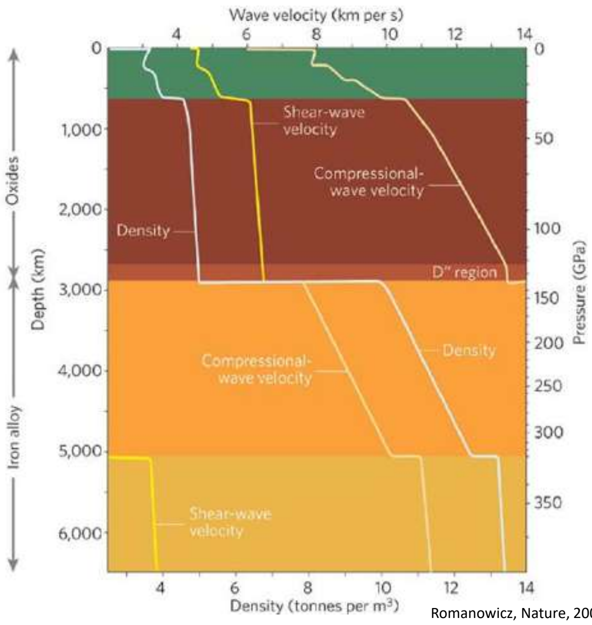
Seismic Waves through Earth's interior

Geologists use a simple labelling scheme to describe the various ray paths taken by seismic waves.
PcP and ScS are compressional and shear waves, respectively, that are reflected by the core.
PP and SS waves are internally reflected from Earth's surface.
A PKP wave travels through the liquid outer core, a PKIKP wave travels through the solid inner core, and a PKiKP wave is reflected by the inner core.



Seismic Waves through Earth's interior

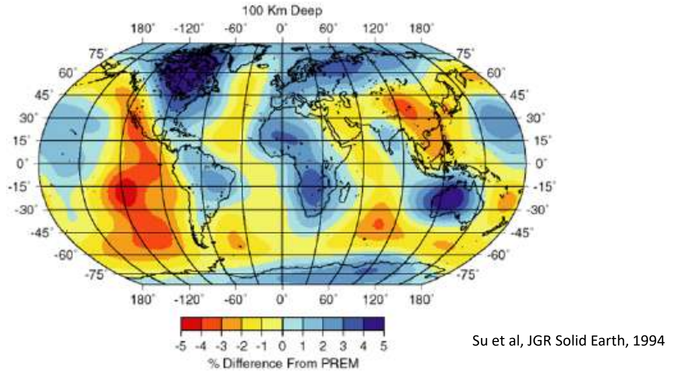
The first-order structural units of Earth — its suite of concentric shells and their approximate composition — were established over the first half of the twentieth century from measurements of the travel times of seismic waves refracted and reflected inside Earth, whereas proof of the solidity of the inner core had to await the capability to record and digitize long time series and measure the frequencies of free oscillations. The '660 km' discontinuity is a phase change, and possibly a compositional change, in the silicate mantle. This illustration is of the Preliminary Reference Earth Model (PREM)



Dziewonski and Anderson, PEPI, 1981

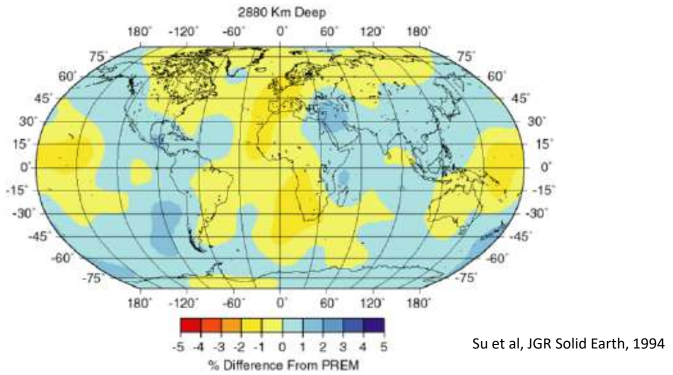
Romanowicz, Nature, 2008

Seismic Waves through Earth's interior



In shallow (~100 km) regions where material is rising from the mantle, it should be warmer, and the velocity should be lower, in regions that are old and cold, such as beneath many of the old parts of continents, we would expect to see faster regions (assuming that temperature is the only difference). The actual variations are influenced by both temperature and composition variations, but they agree well with the ideas of plate tectonics, particularly at the divergent boundaries or oceanic spreading ridges.

Seismic Waves through Earth's interior



Shear wave variations at 2,880 km depth , just above the core-mantle boundary. See the lower-mantle velocity variations are more subdued than those in the more heterogeneous upper mantle. Also, note that the correlation with surface tectonics is gone, as you would expect for a complex convective system such as Earth's mantle.

The Layered Earth

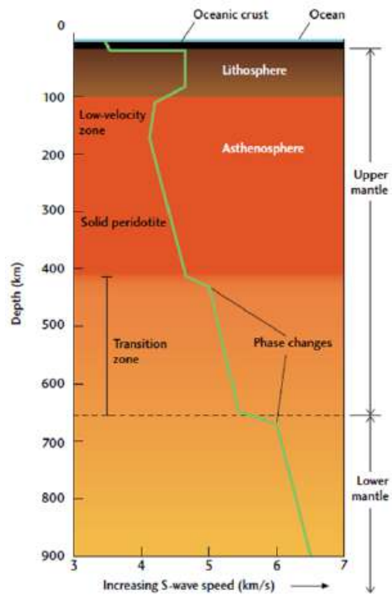
- What are the Compositions?

CRUST

- Felsic rocks typical of the upper continental crust (granite): V_P 6 km/s; 2.6 g/cc
- Mafic rocks typical of oceanic crust or the lower continental crust (gabbro): V_P 7 km/s; 2.9 g/cc
- Ultramafic rocks typical of the upper mantle (peridotite): V_P 8 km/s; 3.3 gm/cc

Mantle

- From MOHO to 410 km (peridotire: iron- and magnesium-rich silicate minerals)
- From 410-660 km (high pressure variations of olivine – the MTZ (Wadsleyite & Ringwoodite)
- From 660-2885 km (Lower Mantle – Perovskite)

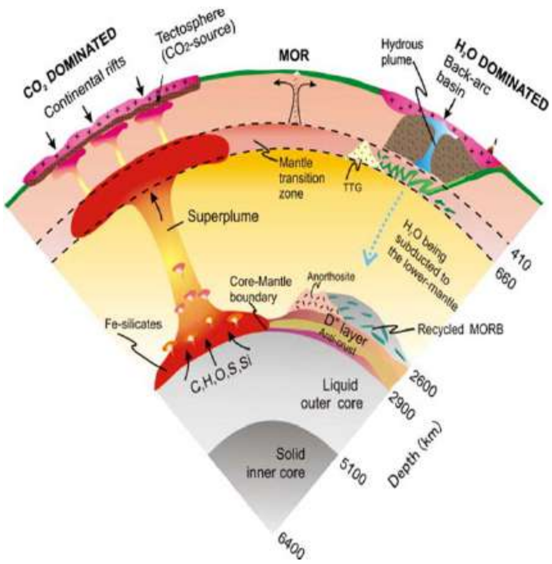


The Layered Earth

- What are the Compositions?

CORE-MANTLE BOUNDARY (CMB)

- Dramatic change in composition; from high pressure solid silicate to liquid Fe-alloy
- The last 200 km at the base of lower mantle (known as D" layer) receive extreme heat and responsible for driving the Mantle Convection.
- Plumes also originate from the CMB.
- This zone is also the graveyard of the subduccted lithosphere.



The Layered Earth

- What are the Compositions?

CORE

- Outer core Liquid and Inner Core Solid.
- Composition is Fe-Ni alloy
- We have very limited information about the core

Next Lecture

Temperature and other related properties

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 30. Mantle Dynamics

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Experimental Rock Deformation Laboratory

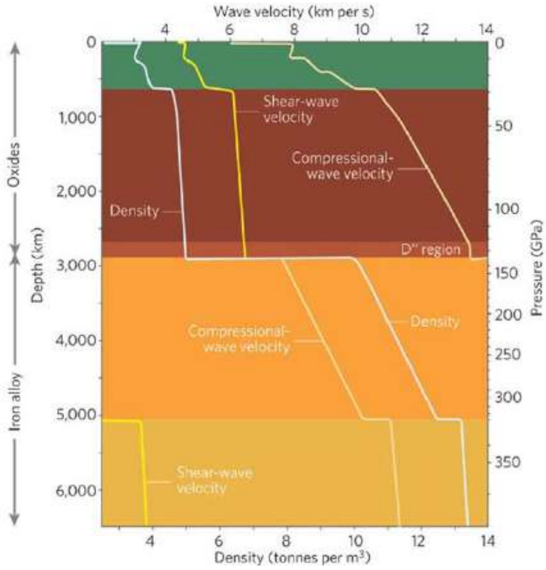
Aims of this lecture

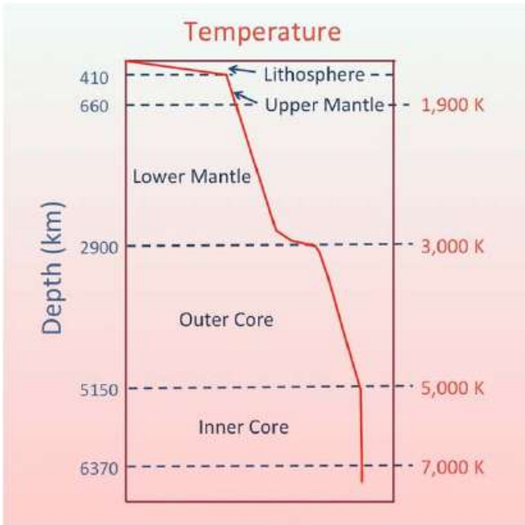
- Earth's Temperature profile
- Heat transfer in Earth's Mantle
- Mantle Convection

Reading:
- Marshak's Book (Chapter 2)
- Grotinger & Jordan's book (Chapter 14)

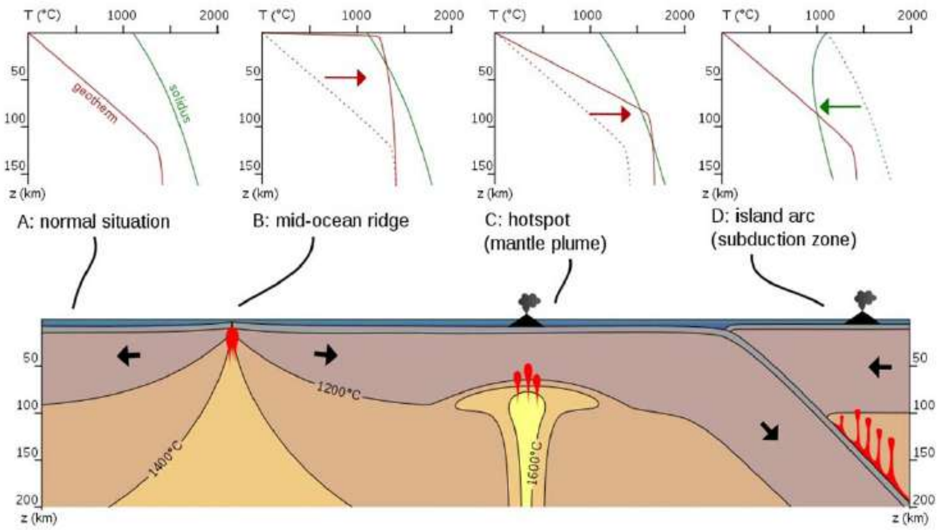
Geodynamics: *Turcotte and Schubert, Chambridge University Press (3rd Ed)*

As a whole





Crust and upper Mantle



Heat conduction through the lithosphere

- The Earth is cooling... losing internal energy.
- Heat is being released from the Earth's interior at a rate of about *44TW/year*. Averaged over the surface of the Earth, this amounts to a heat flow of about *70W/m²* through the crust .
- Heat energy diffuses through the crust and lithosphere by conduction according to Fourier's Law of Thermal Conduction.
- With magmas at volcanoes and spreading ridges, heat is being advected to the surface. Actually, this accounts for only a fraction of the heat that is brought to the surface and radiated through the atmosphere into space.

Fourier's Law of heat conduction

- A rate equation that allows determination of the conduction heat flux from knowledge of the temperature distribution in a medium

$$\vec{q}(\vec{r}) = -k\nabla T(\vec{r})$$

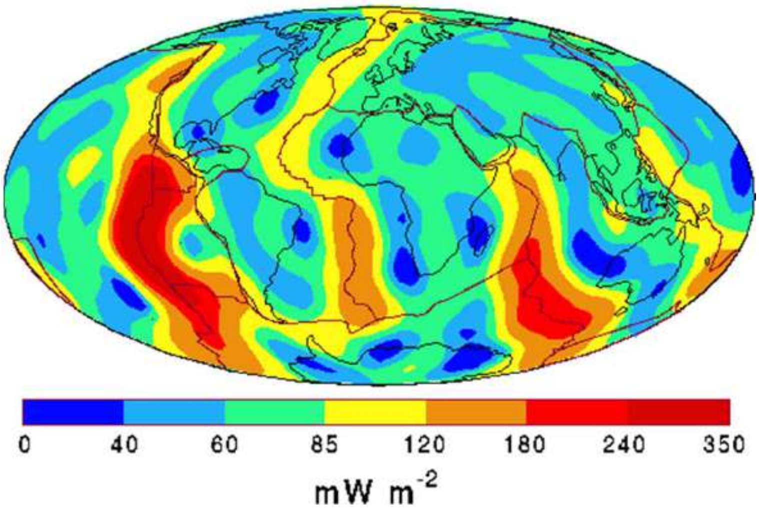
$\vec{q}$: *heat flux* $[W \cdot m^{-2}]$

k: *conductivity* $[W \cdot m^{-2} \cdot K^{-1}]$

T: *temperature* $[K]$

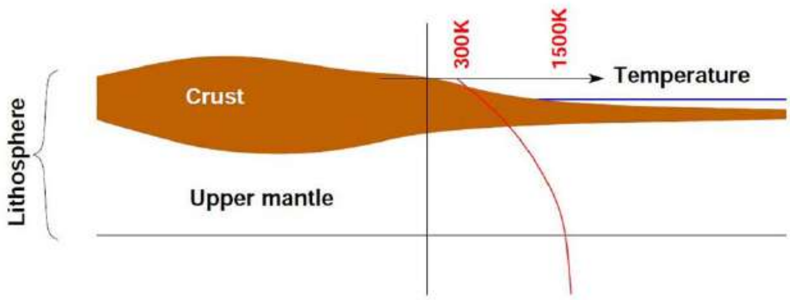
- Heat transfer is in the direction of decreasing temperature (basis for minus sign).
- Direction of heat transfer is perpendicular to lines of constant temperature (isotherms).
- Heat flux vector may be resolved into orthogonal components.
- Fourier's Law serves to define the thermal conductivity of the medium

Global Distribution of Heat Flow



http://geophysics.ou.edu

Temperature through the lithosphere and crust



- For a lithosphere with *100km* depth (i.e., an average gradient of *12K/km*), the average lithospheric thermal conductivity: $k \sim 4\ W\ m^{-2}\ K^{-1}$.
- Measured conductivities of surface rocks: $k \sim 2\text{-}3\ W\ m^{-2}\ K^{-1}$.

Thermal diffusion (conductive)

$$\nabla^2 T(\vec{r},t) + \frac{1}{k} h_i(\vec{r},t) = \frac{1}{D}\partial_t T(\vec{r},t)$$

$$\nabla^2 T(\vec{r},t) = \frac{1}{D}\partial_t T(\vec{r},t)$$

T: *temperature* $[K]$

$D = \frac{k}{\rho C_P}$: *thermal diffusivity* $[m^2 \cdot s^{-1}]$

ρ: *density* $[kg \cdot m^{-3}]$

C_p: *heat capacity at constant pressure* $[J \cdot kg^{-1} \cdot K^{-1}]$

$h_i = \partial_t Q_i$: *rate of heat input/volume* $[W \cdot m^{-3}]$

Q_i: *quantity of heat energy* $[J]$

Thermally driven mantle convection

- The contribution of diffusive cooling of the mantle is insignificant in comparison to convective heat transport through the mantle.
- The mantle behaves like a *viscous fluid* on long timescales; being a fluid, it can flow and can be driven into convection by a temperature gradient.
- Heat flows out of the depths of the cooling Earth transported through the mantle between the D'' layer and the base of the lithosphere by convective fluid motions rather than conduction. This is the more effective means of moving heat through a fluid.

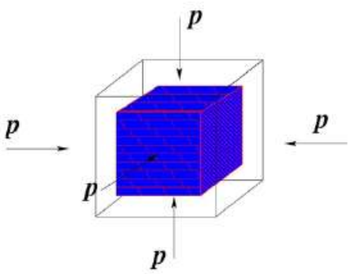
How does convection work?

- It's not conduction! More rapid heat transfer.
- Raise a parcel of hot rock.
- If constant entropy: Lower P => expands => larger volume => decreasing T
- This is known as adiabatic process.

Adiabatic compression

Consider a cube of mantle material under pressure

Energy is received due to work…



$$\Delta T \propto \Delta P$$

$$\propto T$$

$$\propto \frac{1}{\rho}$$

$$\propto \frac{\alpha P}{C_p}$$

T: Temperature
P: Pressure
ρ: Density
α: Thermal expansion
C_p: Heat capacity

$$\Delta T = \frac{\alpha P}{C_p} \frac{T \vec{g} \rho \Delta r}{\rho}$$

Adiabatic temperature gradient

- Need the change of temperature with pressure at constant entropy, ***S***

$$\left(\frac{\partial T}{\partial P}\right)_S = -\left(\frac{\partial T}{\partial S}\right)_P \left(\frac{\partial S}{\partial P}\right)_T$$

Maxwell's thermodynamic relation $\left(\frac{\partial S}{\partial P}\right)_T = -\left(\frac{\partial V}{\partial T}\right)_P$

Coefficient of thermal expansion $\alpha = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P$

Specific heat $mC_p = T\left(\frac{\partial S}{\partial T}\right)_P$

Re-arranging $\left(\frac{\partial T}{\partial P}\right)_S = \frac{\alpha T}{\rho\, C_p}$

Adiabatic *T* gradient as a function of *P*

…. is this sufficient?

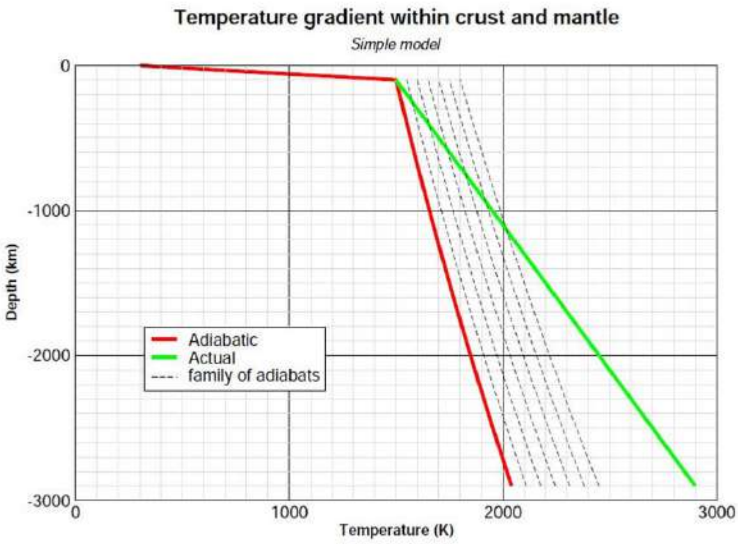
Adiabatic temperature gradient

- $$\left(\frac{\partial T}{\partial P}\right)_S = \frac{\alpha T}{\rho\, C_p}$$ best to have it as function of depth…

For the Earth $\quad \frac{dP}{dr} = -g\rho$

Re-arranging $\quad \boxed{\left(\frac{\partial T}{\partial r}\right)_S = \frac{\alpha\, T\, g}{C_p}}$

Mantle temperature?



If the actual temperature gradient exceeds the adiabatic gradient?

- If the actual temperature gradient (i.e., the increase of temperature with depth) exceeds the local adiabatic temperature gradient, then any infinitesmal displacement of a volume of mantle material will be enhanced through buoyancy, if displaced upwards or negative bouyancy if displaced downwards.
- **We have "*convection*"!**
- The process of convection removes heat from depth in the mantle to the base of the lithosphere where it is conducted out to the surface. The interior cools; the actual temperature gradient reduces.
- The process of convection pulls the entire mantle temperature toward the adiabatic gradient. If the temperature gradient falls to the adiabatic or below, convection ceases!
- If the temperature at the base of the lithosphere is *1500 K* as corresponds to Hawaiian lava eruptions, then the adiabatic gradient to top of the D'' layer would account for a base temperature in excess of about *2100 K* depending on the distributed thermal expansivity, α_p , and heat capacity, C_p, throughout the mantle.
- Heat "conducts" into the fluid mantle through the D'' boundary layer.

Mantle convection

- **In a fluid:**

  Occurs when density distribution deviates from equilibrium

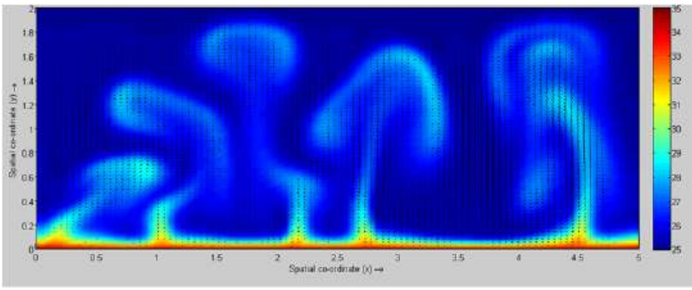
  Fluid may then flow to achieve equilibrium again

- **In a viscous solid heated from below:**

  Initially heat is transported by conduction into the fluid at the base

  Increased temperature reduces the density making the material at the base less dense than fluid above

  Once the buoyancy force due to the density contrast overcomes the inertia of the fluid convection begins

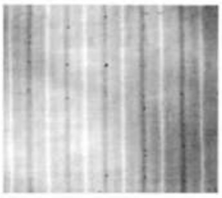


Rayleigh-Bernard convection

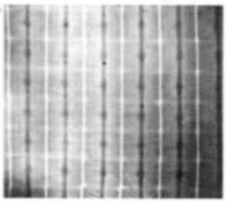
- **Newtonian viscous fluid:**

Stress = dynamic viscosity x strain rate

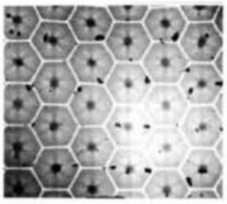
As fluid at the base heats up, initial convection is in 2D rolls



As heating proceeds, a second set of rolls forms perpendicular to the first – *bimodal*



Continued heating – *hexagonal* pattern

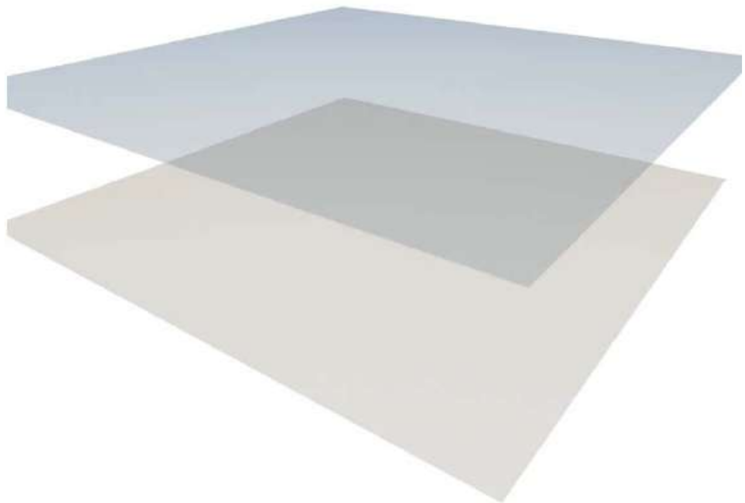


Spoke to irregular pattern

Read:
David White (1988); *The planforms and onset of convection with a temperature-dependent viscosity*; Journal of Fluid Mechanics, 191, 247-286.

Rayleigh-Bernard convection - examples

Rayleigh-Bernard convection - examples



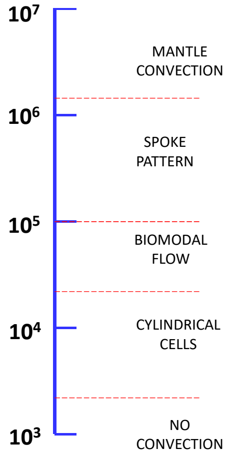
Rayleigh number

- Convection can be *driven* by internal or bottom heating. Surely, both contribute.
- The Rayleigh number measures the ratio of the forcing-to-retardation of the convection. A nondimensional number which describes the nature of heat transfer by suggesting the relationships between buoyancy and viscosity with a fluid
- For internal heating: $$Ra = \frac{g\rho^3 \alpha h_i d^5}{\eta k D}$$
- For bottom heating: $$Ra = \frac{g\rho^2 \alpha C_p T_{sx} d^3}{\eta k}$$

η is the local viscosity,
T_{sx}, the local adiabatic excess.
D is mantle thickness, base of lithosphere to D''.

- **The critical Rayleigh number:**
  - The point at which convection initiates
  - Approximately > 10^3 (dependent on geometry)
  - By knowing the material properties and physical geometry we can determine if there will be convection and the nature of that convection

Rayleigh number and convective mode



Rayleigh number of the mantle:

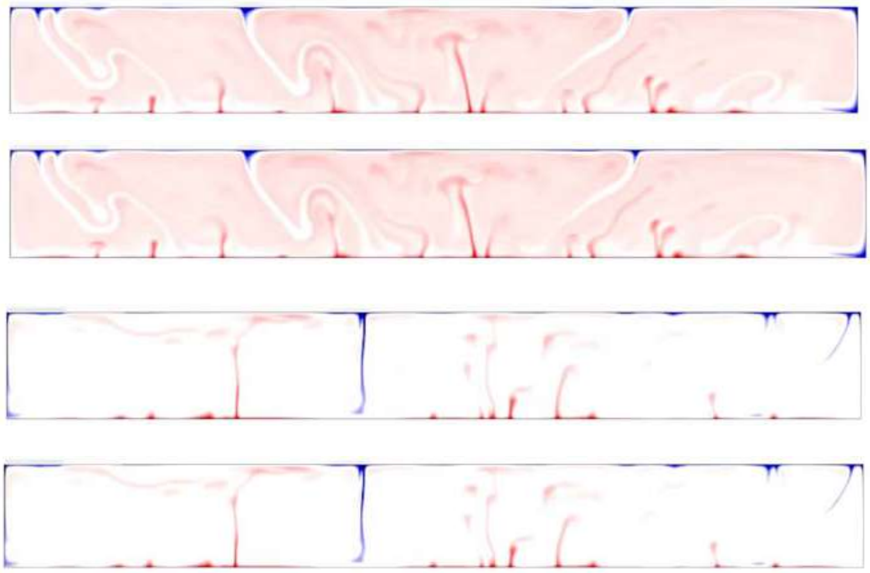
Upper mantle (thickness 700 km): 10^6

Lower mantle (thickness 2000 km): 3×10^7

Whole mantle (thickness 2700 km): 10^8

Mantle convection – temperature dependence of Viscosity

Ra	10^7
T of viscosity*	1000 x
η increase @ 660	0
Internal heating	0
Ra	10^7
T of viscosity*	100 x
η increase @ 660	0
Internal heating	0
Ra	10^7
T of viscosity*	10 x
η increase @ 660	0
Internal heating	0
Ra	10^7
T of viscosity*	0 x
η increase @ 660	0
Internal heating	0



* Temperature dependence of Viscosity: --- x contrast between hottest and coldest

Mantle convection – Rayleigh number variation

Ra 10^8
T of viscosity 1000 x
η increase @ 660 0
Internal heating 0

Ra 10^7
T of viscosity 1000 x
η increase @ 660 0
Internal heating 0

Ra 10^6
T of viscosity 1000 x
η increase @ 660 0
Internal heating 0

Ra 10^5
T of viscosity 1000 x
η increase @ 660 0
Internal heating 0

* Temperature dependence of Viscosity: --- x contrast between hottest and coldest

Mantle convection – variation due to internal heating

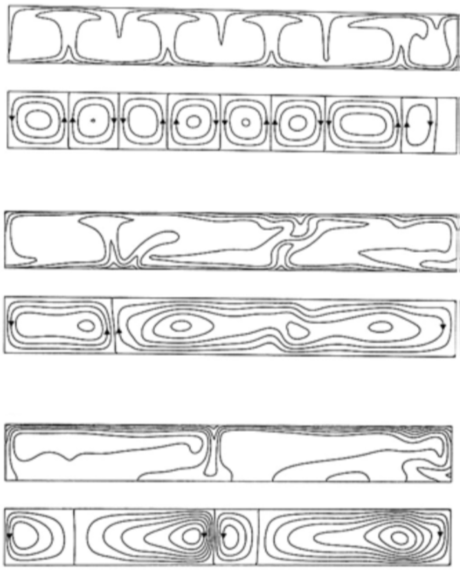
Ra 10^7
T of viscosity 1000 x
η increase @ 660 0
Internal heating 0

Ra 10^7
T of viscosity 1000 x
η increase @ 660 0
Internal heating 20

Ra 10^7
T of viscosity 1000 x
η increase @ 660 0
Internal heating 40

* Temperature dependence of Viscosity: --- x contrast between hottest and coldest

Mantle convection – the effect of heating - summary



Heat from below
T is fixed on upper boundary

Aspect ratio of 1
… not what we see on Earth

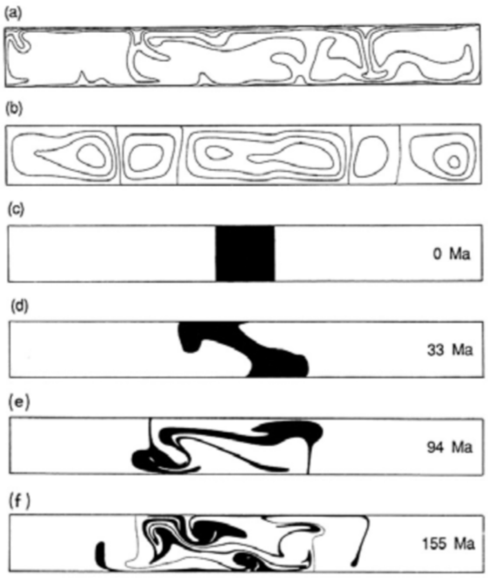
Heat from below
Constant heat flow across upper boundary

Large aspect ratio
… realistic?

Internal heating only

No upwelling sheets

Mantle convection – the effect of heating - summary

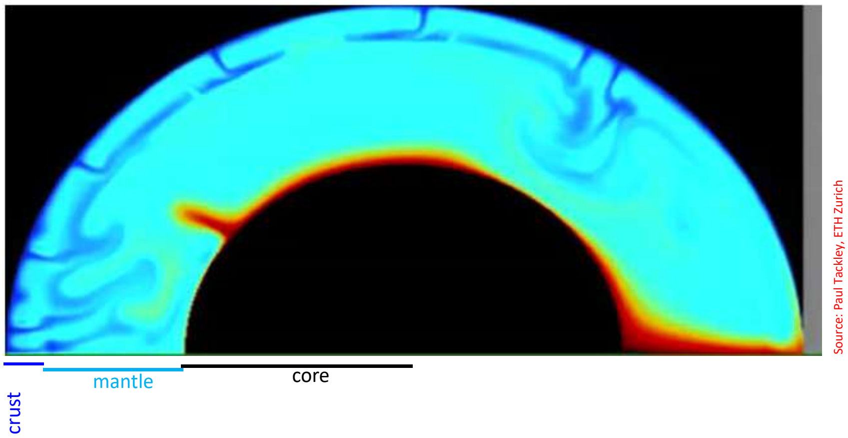


Isotopic ratios of oceanic basalts are very uniform but different from bulk earth values

The mantle is well mixed

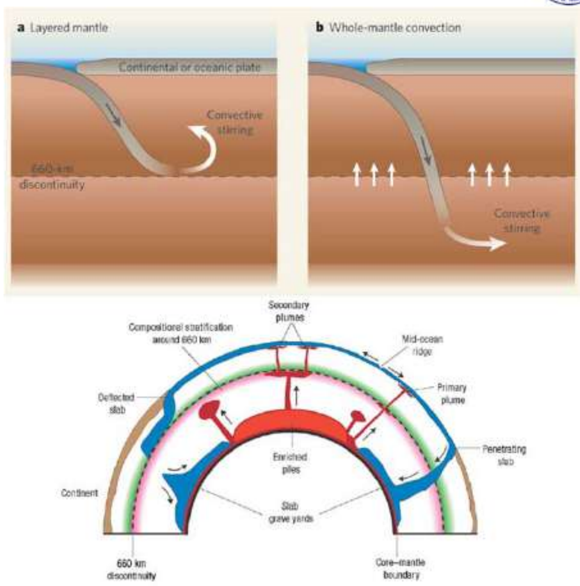
Any body smaller than 1000 km is reduced to less than 1 cm thick in 825 Ma !

Mantle convection – A near perfect combination



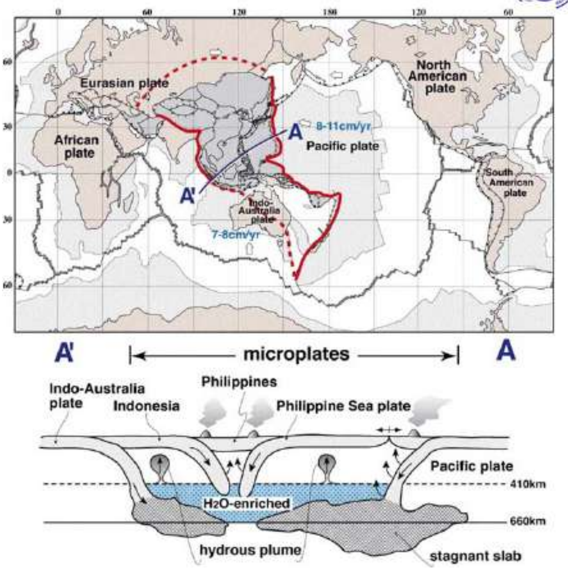
Layered mantle convection?

- There is/was a long-standing debate concerning the possibly layered convection in the mantle.
- There is general agreement that the 660 km phase change does retard sinking subducting plates and bouyant rising melts during convection
- There is also general agreement that plates can and do penetrate through 660 and that rising plumes and convective sheets rise through 660.
- Seismic tomography shows that we have a pooling of material around 660 as would be expected of layered convection while there remains sufficient penetration to involve the whole mantle in the convective process.



Stratified mantle

- In East Asia, the old Pacific plate subducts from the east, and the Indo-Australia plate from the south (double-sided subduction zone).
- The upper and lower mantle here are the coldest mantle regions in the world.
- This is the most active region on the Earth, indicating that the role of water is several orders of magnitude higher than that of the temperature in terms of lowering viscosity and drop of solidus. Note also the predominant occurrence of microplate in this region. Not only the fragmentation of continents but also the formation of small oceans constitutes the major reason for the dominant occurrence of microplates.
- The schematic cross-section of WPTZ is shown below to illustrate the stagnant slabs, hydrous MBL, and formation of hydrous plumes at 410 km depth by the breakdown reaction of hydrous wadsleyite enriched in incompatible elements



Some questions…

- Earth has mantle convection and plate tectonics – Why?
- When did it start? How long it will continue?
- What about other planets?

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 31. Natural Hazards - Introduction

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Experimental Rock Deformation Laboratory

Aims of this lecture

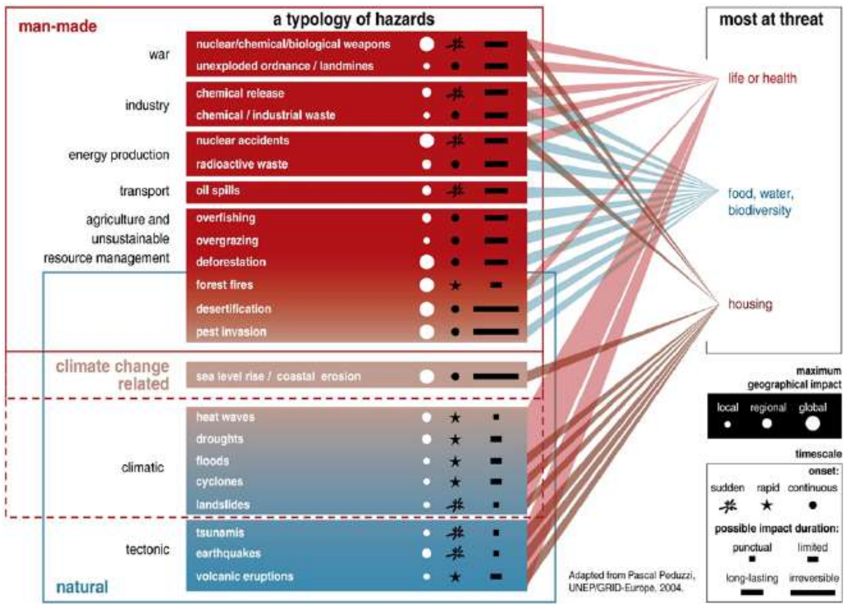
- What is Natural Hazard?
- Some data and Statistics

The concept of Natural Hazards

- "Events associated with normal geological or biological processes and widespread technological accidents that cause death, injury or loss of home, property or income".

The intensity of the hazard may be influenced by human modifications of the landscape (*e.g., deforestation and urbanization influence flood frequency and magnitudes*) or climate (*e.g., heat waves in urban areas*).

The concept of Natural Hazards



Source: Emmanuelle Bournay; UNEP/GRID-Arendal

Classification of Hazards

Natural and anthropogenic accidents may be classified by the inducing factors

Atmospheric factors
Hydrologic factors
Geological factors
Biological factors
Technological Factors
Social violence
Complicated danger factors

The concept of Risk

RISK = HAZARD X VULNERABILITY

Hazard: Natural processes capable of causing death and/or destruction;

Vulnerability: Social or economic sensitivity to the effects of hazards

The concept of Risk

Example 1: same hazard; contrasting vulnerabilities

Magnitude 6.5 earthquake in south-central California, on Dec. 22, 2003: 7 dead, ~50 injured because the event occurred in a thinly inhabited area (low risk event).

Magnitude 6.5 earthquake in city of Bam (Iran) on Dec. 26, 2003: ~40,000 dead, ~30,000 injured; much of the city destroyed (very high risk event).

The concept of Risk

Example 2: contrasting hazards; same risk

Severe snowfall in the Lower Mainland, British Columbia

Annual risk (\$) = $P_{blizzard}$ X Cost*
= 0.1 X \$10 M? = \$1 M

"Tunguska" asteroid impact in the Lower Mainland, British Columbia (1908)

Annual risk (\$) = P_{impact} X Cost*
= 0.000001 X \$100 M? = \$1 M

*Costs = deaths, injuries, building collapse, rescue, cleanup, lost production, rebuilding, etc. (often very difficult to assign a dollar value).

The concept of Risk

Combating Risk

Pre-Event

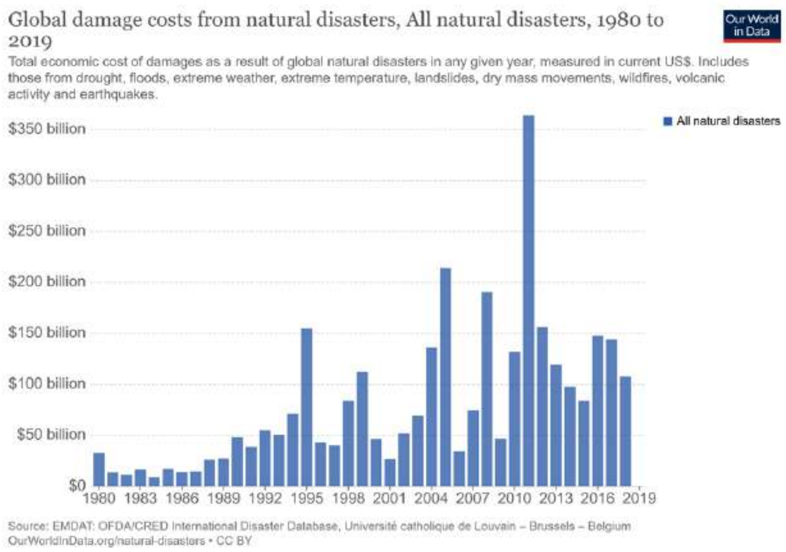
Assess: characterize the hazard regime;
Mitigate: reduce vulnerability;
Prepare: educate; warn; evacuate;

Post-Event

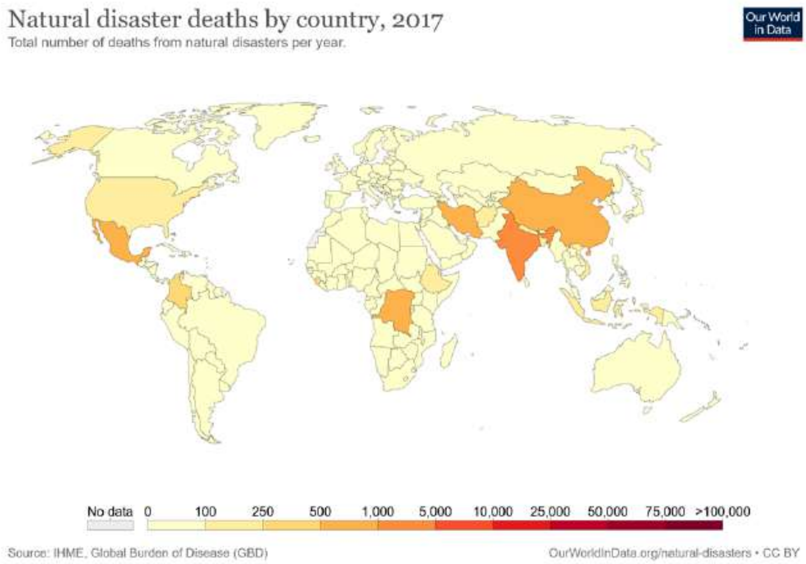
Respond: remove bodies, locate and treat survivors, destroy unstable structures;

Recover: rebuild communities and infrastructure

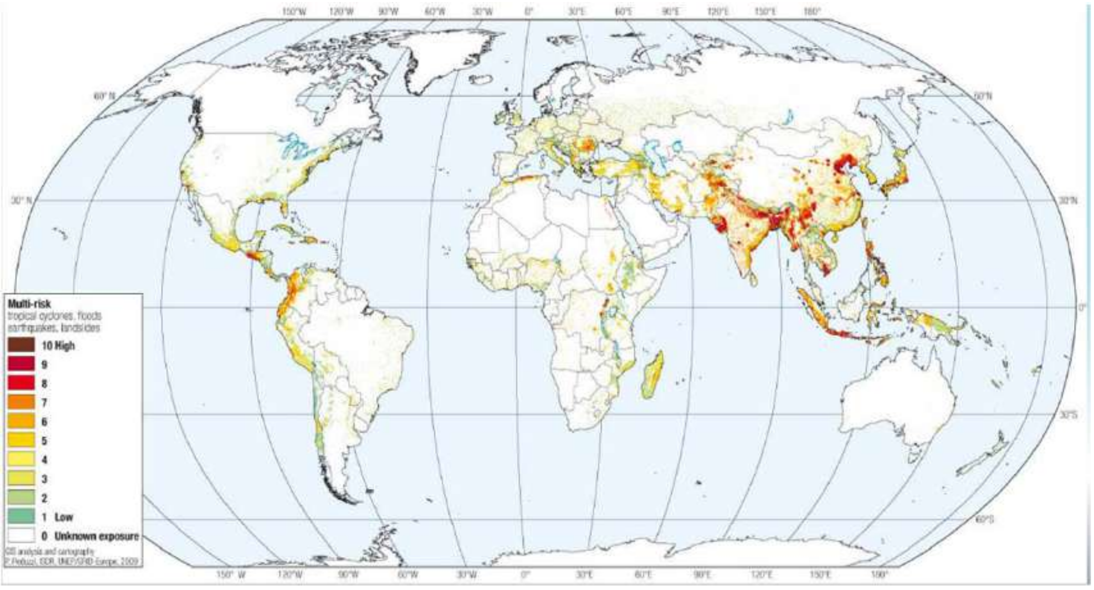
Some data related to Hazard, Damage and Risk



Some data related to Hazard, Damage and Risk

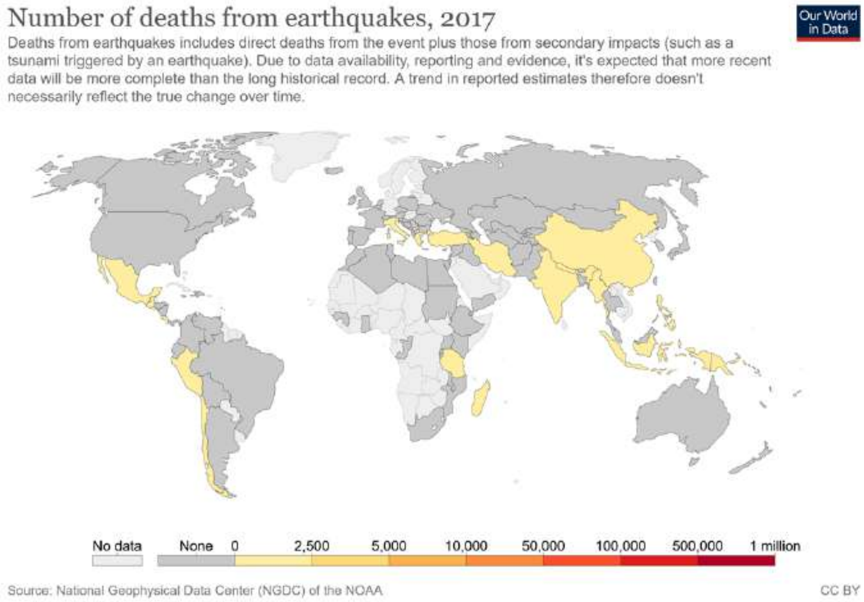


Some data related to Hazard, Damage and Risk

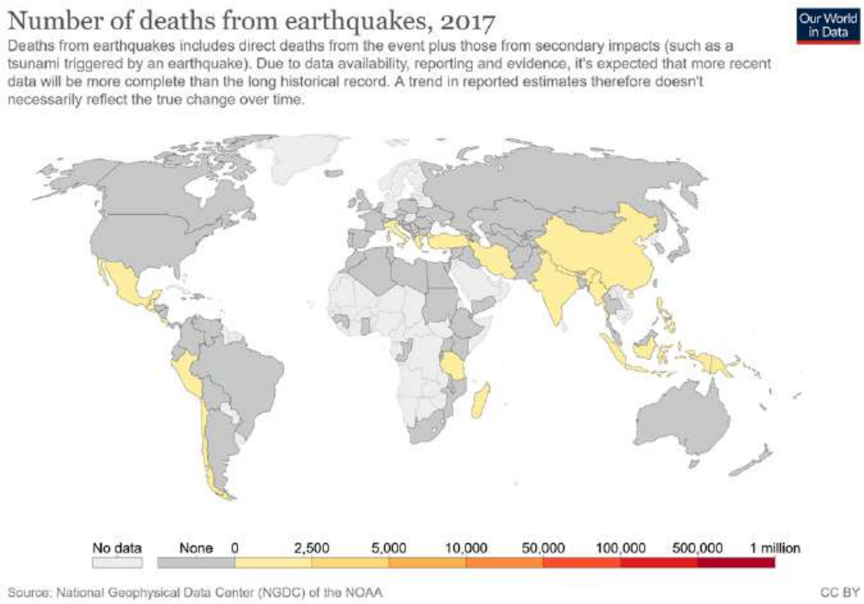


According to the probability of death rates

Some data related to Hazard, Damage and Risk



Some data related to Hazard, Damage and Risk



Physical Expressions of Hazards

Direct effects are effects that appear immediately after the disaster

Indirect effects appear later and sometimes can be difficult to identify and link up with a disaster

Tangible effects are those for which it is possible to estimate losses in monetary terms, such as the damaged property to restore the necessary resources

Undetectable effects are actual effects, but impossible to determine in monetary expression (loss of life can be detectable medically and legally, but economical or financial loss value calculation is very complex)

Some common Natural Hazards

Earthquakes

Earthquakes' primary effects are associated with the earth shake, and vertical or horizontal ground movements.

This leads to a strong impact on people and structures.

Secondary effects of earthquakes are associated with rock mass movement, such as **Rock falls** & **Landslides**.

Tsunami **Flood** **Biological Hazards (pandemics etc.)**

Some common Natural Hazards

Volcanoes

Fire

Infectious diseases

Heat Waves

Drought

Thunderstorms, Hurricanes, Tornados

Next Lecture

Earthquakes

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 32. Earthquakes - I

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Causes of Earthquake
- Historical Developments
- Faults
- Earthquake Terminologies

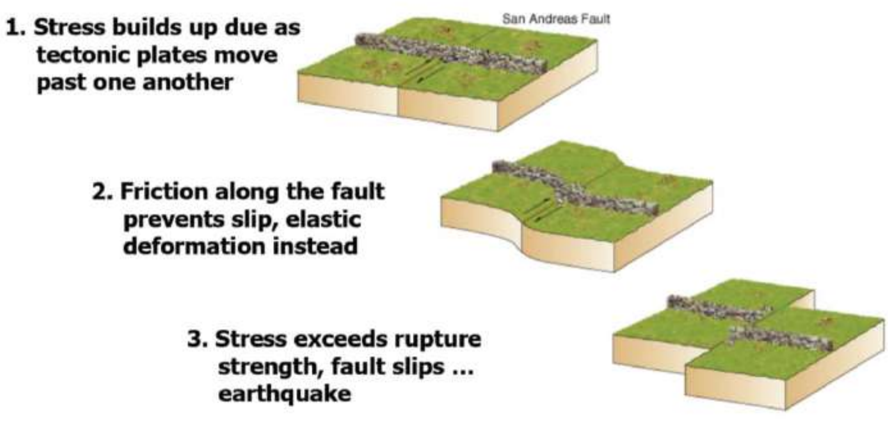
What is an earthquake?

- Release of stored energy (where?)

  - **Elastic rebound theory** explanation to how earthquakes occur
  - Plate movement concentrates energy in crust
  - When the stored energy exceeds the strength of the crust, the crust ruptures
  - The rupture generally occurs along faults (existing or new?) because this is the weakest point

What is an earthquake?

...the release of built-up stress along faults

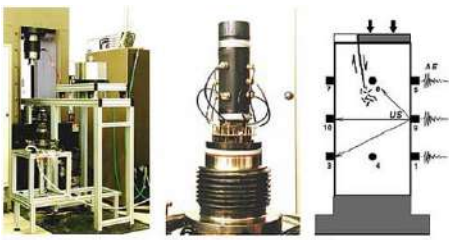


→ Elastic rebound theory: developed in the Lawson Report

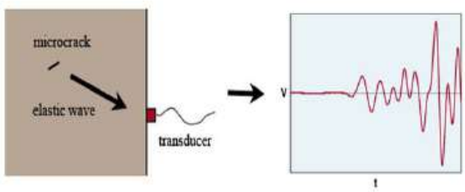
How Faulting Generates Earthquakes?

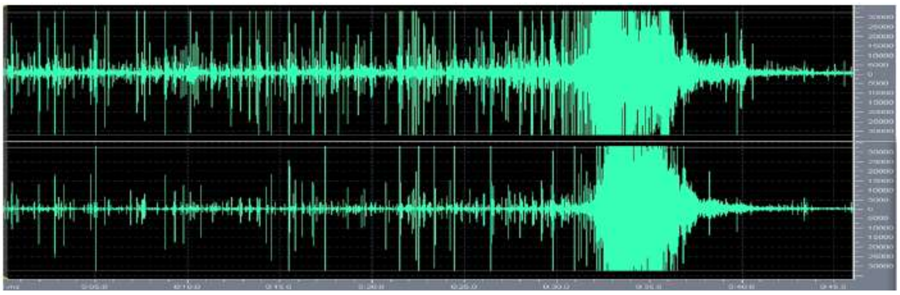
- Movement on the fault causes a release in energy
- As the energy passes through an area, the vibration is felt
- The energy is transferred through the earth and man-made structures
- The bigger the amount of slip the more energy released and therefore, the more vibrations are produced

Energy during faulting – an analogue "*visualization*"



(a) (b) (c)





What are the causes of Earthquakes

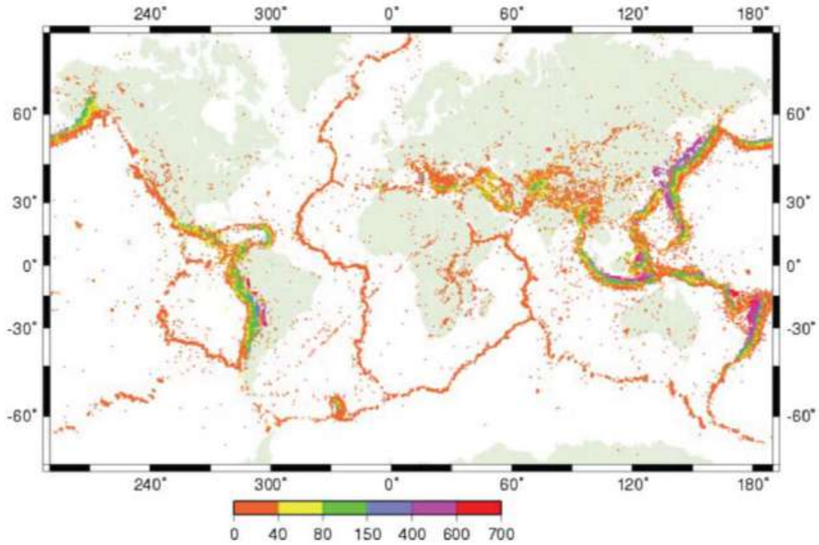
- **Tectonic stress** (most common)
- Water/disposal added under pressure (man-made)
- **Geothermal gradient** (variation due to boundary)
- Rock type
- Fast/Cold and slow/warm (brittle or ductile)

Where do Earthquakes occur

- Historic Records

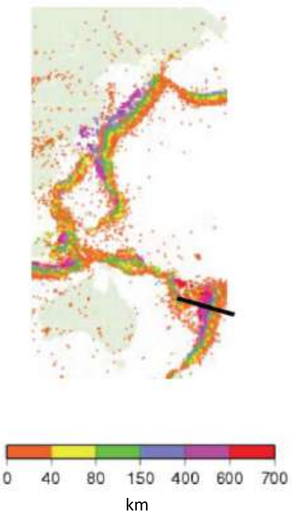
Where do Earthquakes occur

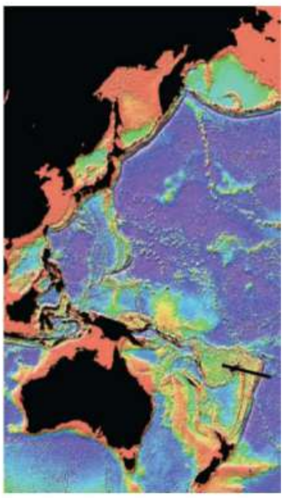
- Now we know, where…

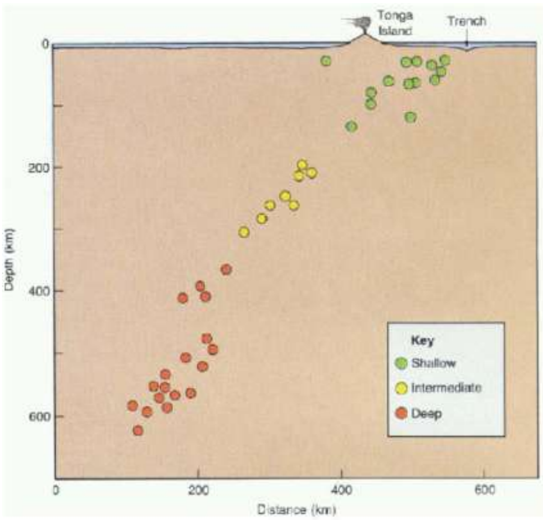


Where do Earthquakes occur

Deep earthquakes







Historical development - I

- Mythology: associated with giant creatures

- Japan: CATFISH
- China: FROG
- Philippines: SNAKE
- Native Indians: TURTLE

.. and yes, it generally happens when **HE** is angry and people do something bad to make him more angry.

Historical development - II

- First Theory: Aristotle was the first one, to suggest a theory..

Gedruckt zu München/bey Adam Berg.
Mit Röm: Keyser: Mayest: Freyheit.

Strong winds blew through caves inside the Earth, creating "*effects similar to those of the winds in our bodies whose force when it is pent up inside us can cause tremors and throbbing*."

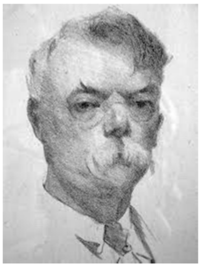
Historical development - III

- A movie with no sound…

- 1906 San Francisco April, 18th
- M: 7.8
- ~3000 death
- 80% of the city destroyed and burnt

Historical development - IV

- A turning point for earthquake science – 1906 San Francisco Earthquake



- **Andrew Cowper Lawson** (July 25, 1861–June 16, 1952)
  - Cataloged descriptions of earthquake effects
  - Identified San Andreas Fault
  - Earthquakes associated with faults
  - Maps of the fault location and ground shaking distribution
  - Elastic rebound theory

Faults

- What are faults?

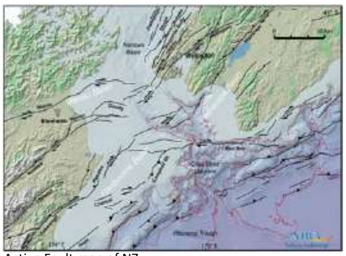
Fault produced during 1930 Napier Earthquake, NZ (Photo: S. Misra)

Guatemala (Photo: Rich Allen, UCB)

California (Photo: Rich Allen, UCB)

- What are ACTIVE faults?

  A fault that has moved at least once in last 11000 years is an ACTIVE FAULT.



Active Fault map of NZ

- What are fault ZONES?

  Areas within 50 feet of identified / mapped active fault.

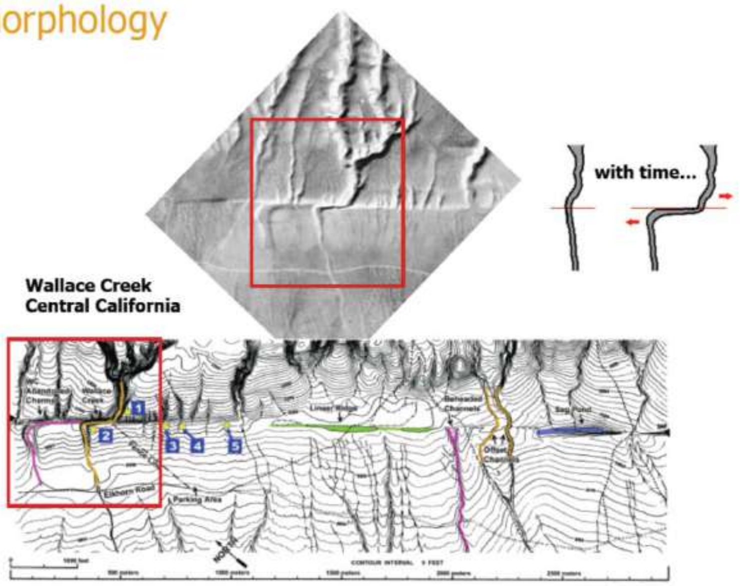
Active Faults

Still active?

Kuangfu Middle School
1999 Chi-Chi earthquake, Taiwan

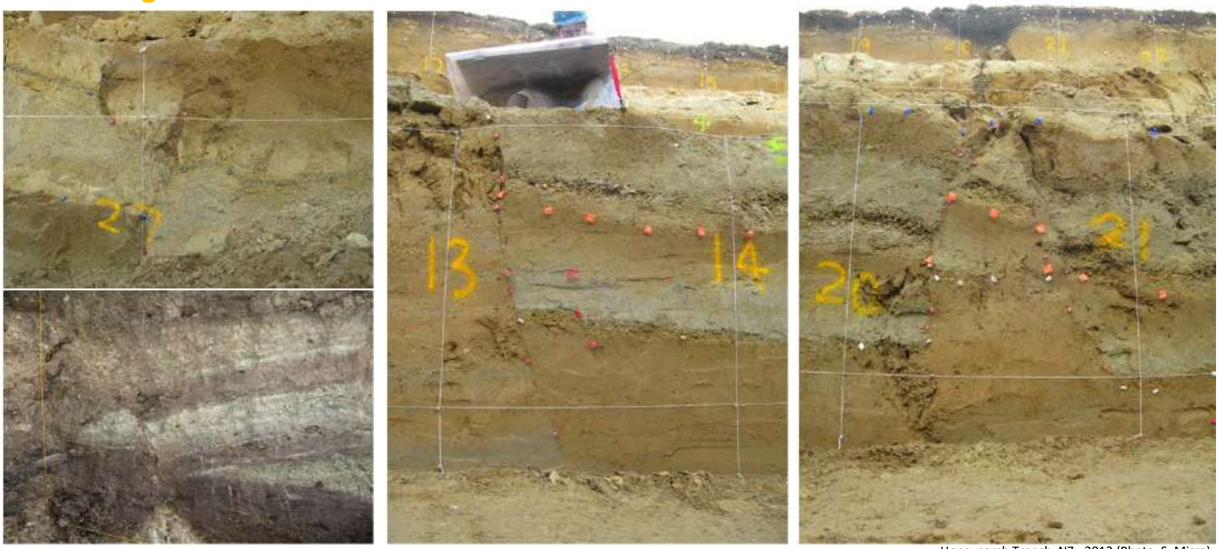
Faults

Geomorphology



Faults

Trenching

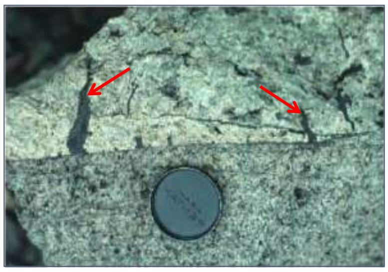


Honeycomb Trench, NZ - 2013 (Photo: S. Misra)

High-speed fault movement - PSEUDOTACHYLITE

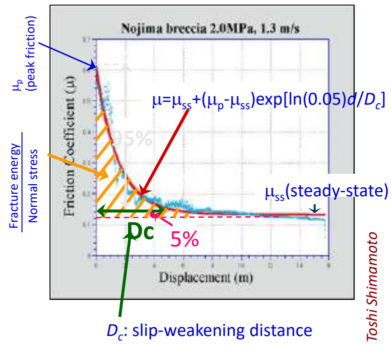
Finding a fossilized Earthquake in Nagaland (S. Misra as scale)

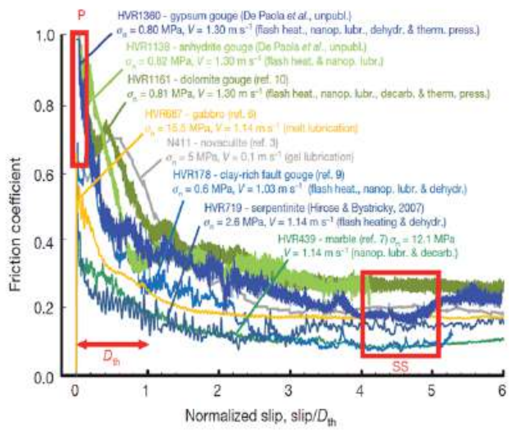
Pseidotachylite in Serpentinite (Photo: S. Misra)



Pseidotachylite in gabbroic rock 2015 (Photo: G. Di Toro)

High-speed fault movement - PSEUDOTACHYLITE





Di Toro et al., 2011; Nature

High-speed fault movement - PSEUDOTACHYLITE

High velocity Rotary Shear Apparatus

Some terminologies…

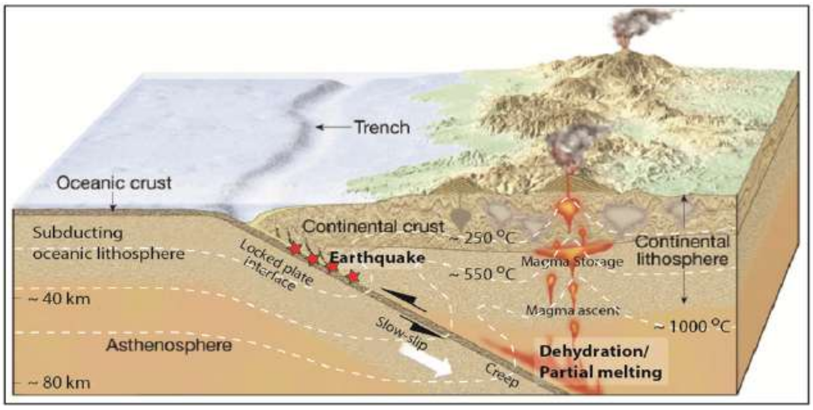
- Normal / Reverse / Thrust / Strike-slip/ oblique Faults
- Fault plane / Fault trace / Dip / Hanging and Foot walls
- Focus / Hypocenter / Epicenter
- Foreshocks and Aftershocks
- Seismic waves
- Shear Wave Splitting (fast and slow arrival)
- Earthquake / Seismic Cycle
- Earthquake Source Mechanism (beach ball)
- Ground Motion

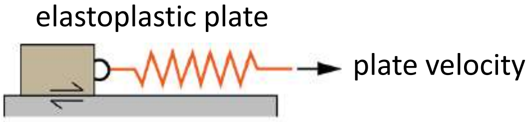
Some terminologies…

- Normal / Reverse / Thrust / Strike-slip/ oblique Faults
- Fault plane / Fault trace / Dip / Hanging and Foot walls
- Focus / Hypocenter / Epicenter
- **Foreshocks and Aftershocks**
- **Seismic waves**
- **Shear Wave Splitting (fast and slow arrival)**
- **Magnitude**
- Earthquake / Seismic Cycle
- **Earthquake Source Mechanism (beach ball)**
- Ground Motion

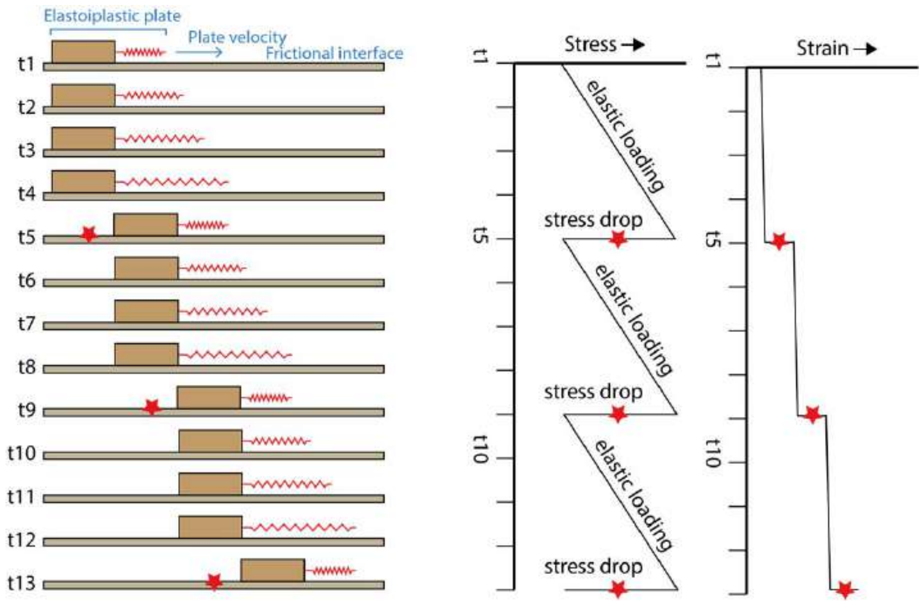
■ **.. In the next lecture**

Earthquake Mechanics – simple model

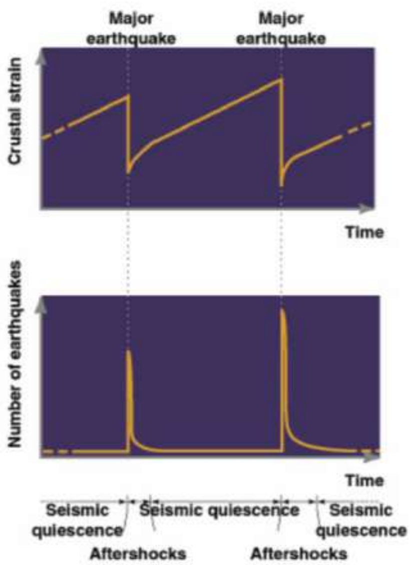




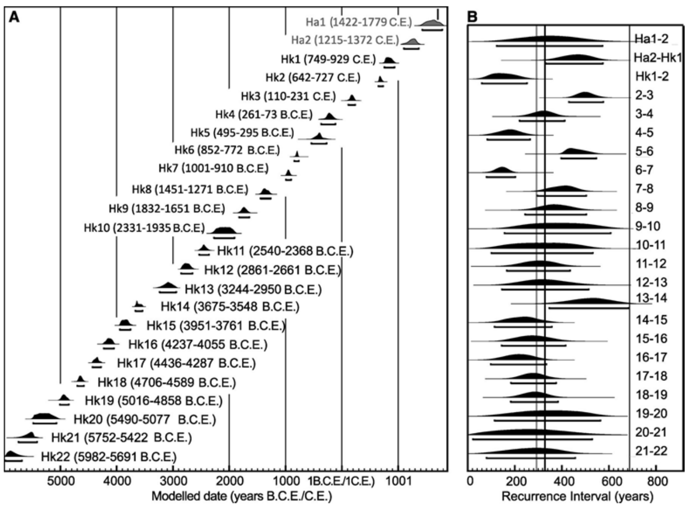
Example I: Rebound due to deglaciation



Earthquake cycle…



Ages of surface-rupturing earthquakes on the Alpine Fault



Details are here: http://www.sciencemag.org/content/336/6089/1690.full.pdf

What should you do if there is an earthquake and you are feeling it?

??

Run away from the building?

Pray to god

Post in social media

Mark yourself safe in social media

Call a friend and share

What should you do if there is an earthquake and you are feeling it?

DROP

COVER &

HOLD ON

Next Lecture

More on Earthquakes

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 33. Earthquakes - II

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Experimental Rock Deformation Laboratory

Aims of this lecture

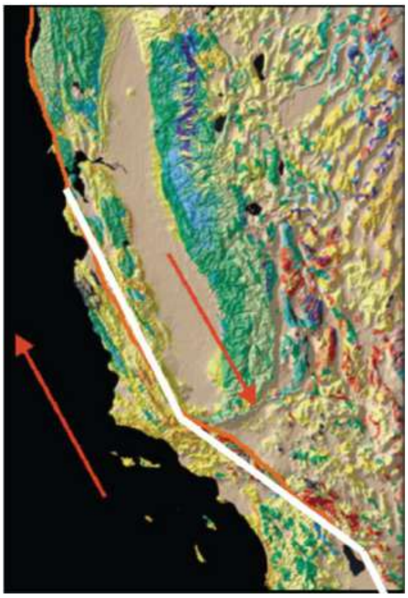
- Visualization of rupture
- Seismic Waves
- Focal Mechanism
- Magnitudes

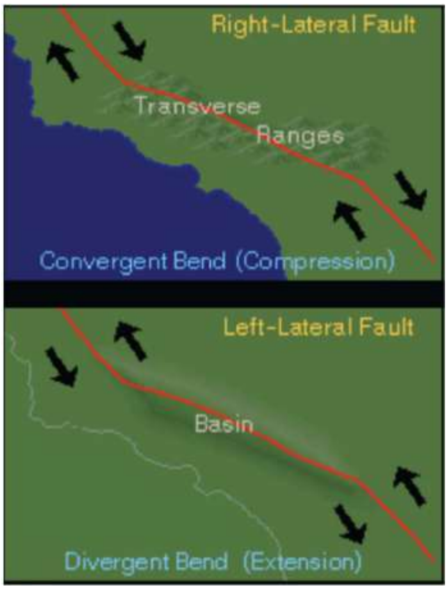
Faulting – how do we see the process

Northridge earthquake

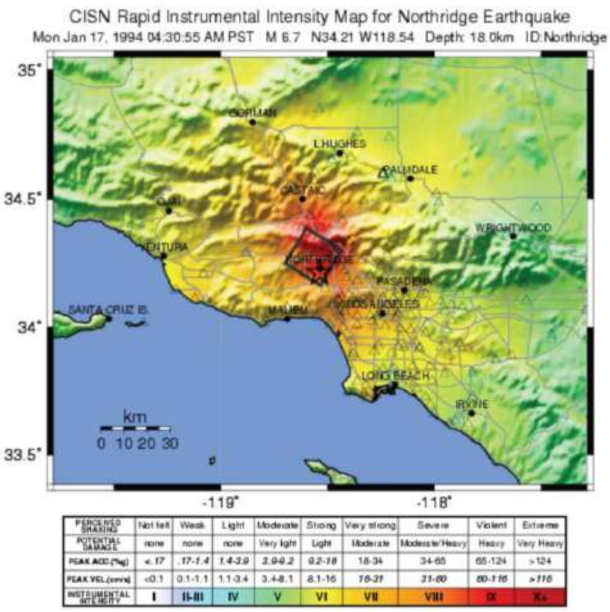
- LA region
- January 17, 1994
- M 6.7
- 56 dead
- 1500 seriously injured
- 12,500 structures damaged
- cost $15 billion

The bend

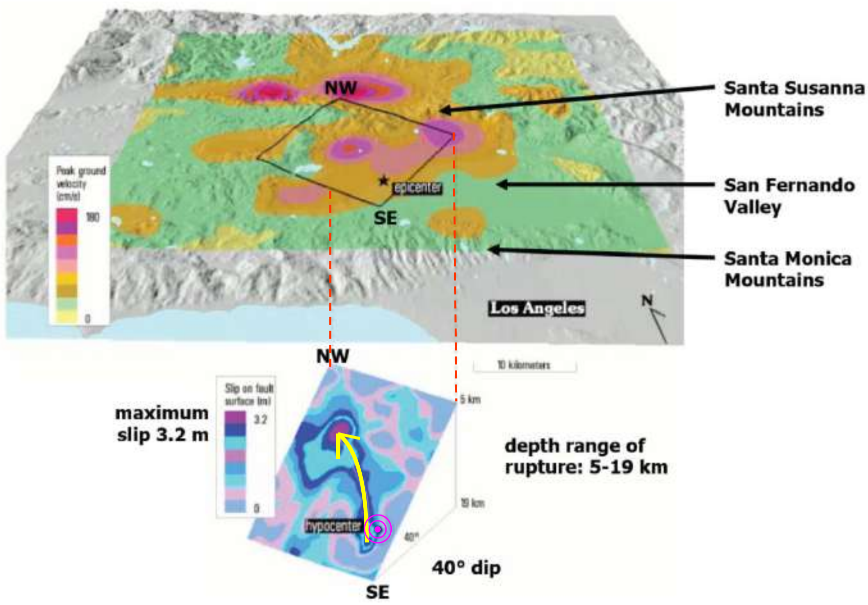




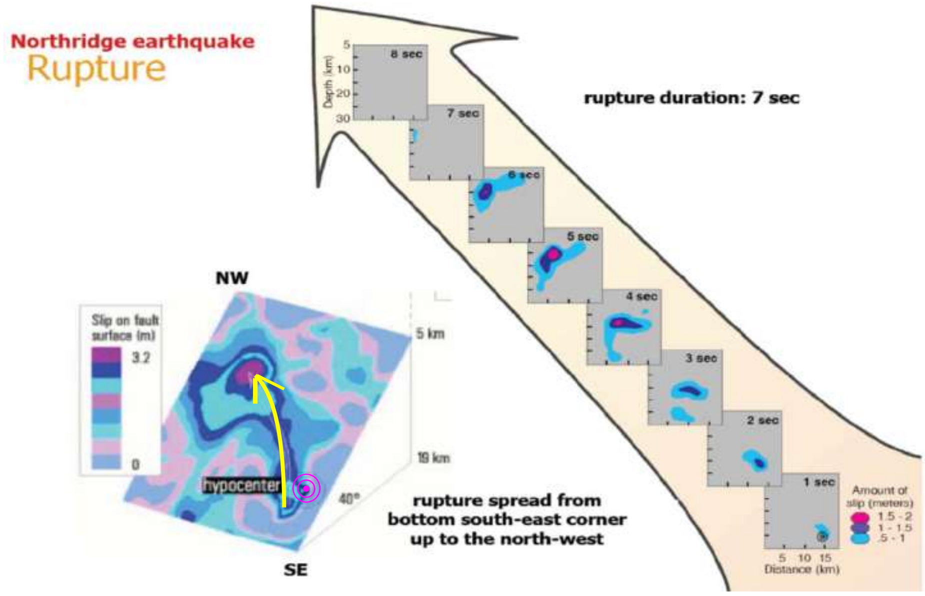
How Faulting Generates Earthquakes?



Ground motion map

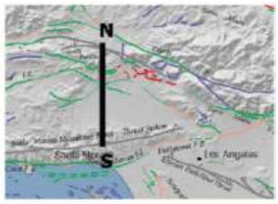


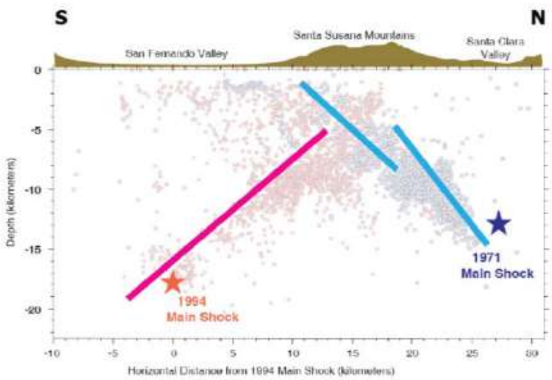
Rupture propagation



Thrust Fault

Compressional setting (NS)





Summary



Photo: Pilar Vilamore, Zabe Bruce and S. Misra

Summary

Photo: Tim Little

Summary

Photo source: Otago University Archive, NZ

Summary

Areal photo: GNS Science, New Zealand

Summary

Areal photo: GNS Science, New Zealand

Summary

Do you a pattern in the fracture?

Can you suggest the stress direction?

Photo: S Misra

Summary

Liquefaction

Photo: S Misra

Summary

Liquefaction

Photo: S. Elis

Summary

Liquefaction

Photo: S Elis

Summary

Landslide

Photo: Z Bruce

Summary

Rock-fall

Photo: J Thomson

Seismic Waves

- **How does the Earth Vibrate?**

Equations of motion
($F = ma$)

Elasticity relations
($\sigma_{ij} = \lambda \varepsilon_{jj} \delta_{ij} + 2\mu \varepsilon_{ij}$)

Elastic wave equations, describing the motion of waves through the Earth

Body waves (P and S)

Surface waves (Love and Rayleigh)

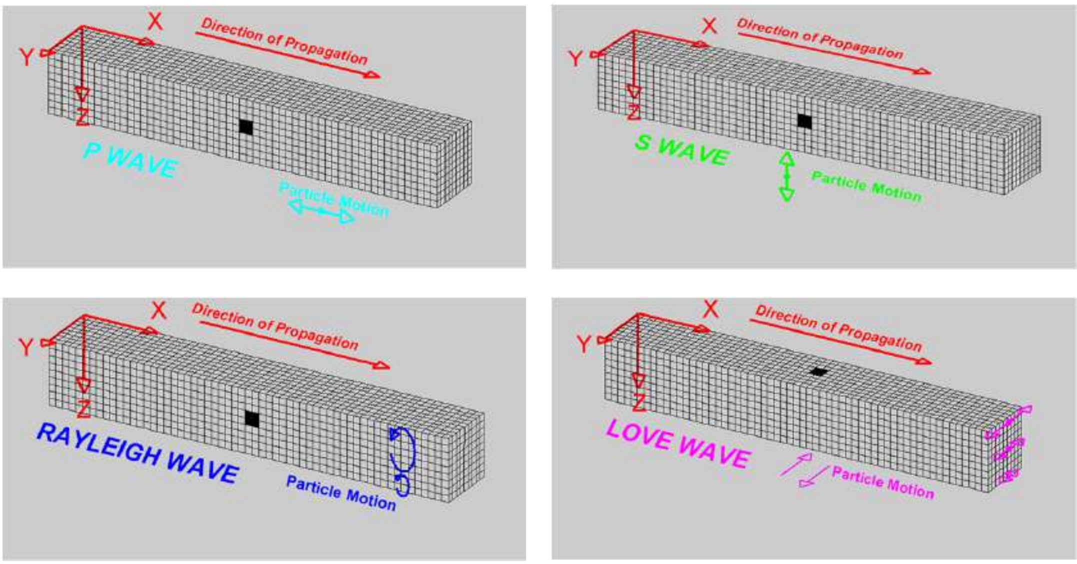
Normal modes (torsional and spheroidal)

$$V_P = \alpha = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \qquad V_S = \sqrt{\frac{\mu}{\rho}}$$

Seismic Waves

Known Elastic Constants	E	ν	μ	κ	λ
Shear modulus μ, Bulk modulus κ	$\frac{9\kappa\mu}{3\kappa+\mu}$	$\frac{3\kappa-2\mu}{6\kappa+2\mu}$	μ	κ	$\frac{3\kappa-2\mu}{3}$
Young's modulus E, Poisson's ratio ν	E	ν	$\frac{E}{2(1+\nu)}$	$\frac{E}{3(1-2\nu)}$	$\frac{E\nu}{(1+\nu)(1-2\nu)}$
Young's modulus E, Shear modulus μ	E	$\frac{E-2\mu}{2\mu}$	μ	$\frac{E\mu}{3(3\mu-E)}$	$\frac{\mu(E-2\mu)}{3\mu-E}$
Young's modulus E, Bulk modulus κ	E	$\frac{3\kappa-E}{6\kappa}$	$\frac{3\kappa E}{9\kappa-E}$	κ	$\frac{3\kappa(3\kappa-E)}{9\kappa-E}$
Shear modulus μ, Lame's constant λ	$\frac{\mu(3\lambda+2\mu)}{\lambda+\mu}$	$\frac{\lambda}{2(\lambda+\mu)}$	μ	$\frac{3\lambda+2\mu}{3}$	λ

Seismic Waves



http://web.ics.purdue.edu

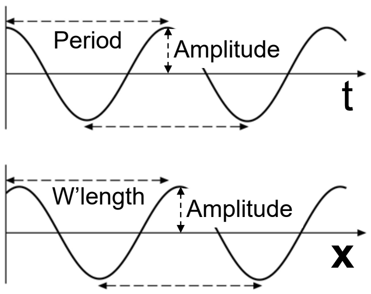
Wavelength, Period and frequency

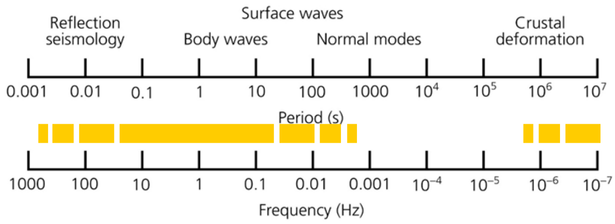
Wavelength (metres, m)
The distance between successive peaks/troughs

Period (seconds, s)
The time between successive peaks/troughs passing a point

Frequency (Hertz, Hz = s^{-1})
The number of oscillations in a fixed time

Amplitude (metres, m)
The wave height measured with respect to the rest position

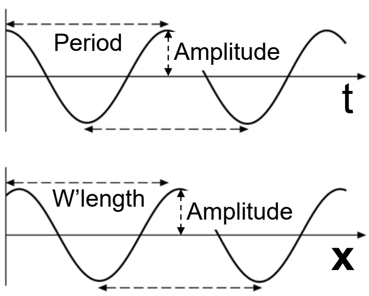




Harmonic wave parameters

Parameter	Symbol	Units	Key relationships
Frequency	f	Hz	$f = \omega/2\pi = 1/T$
Period	T	s	$T = 1/f = 2\pi/\omega$
Wavelength	λ	m	$\lambda = v/f$
Velocity	v	m s^{-1}	$v = f\lambda$
Angular frequency	ω	s^{-1}	$\omega = 2\pi f = 2\pi/T$
Angular wavenumber	k	m^{-1}	$k = \omega/v$

Shearer (1999; Table 3.1)



How to record earthquake generated seismic waves

- **Challenges**

How do we measure ground motion using an instrument that is itself attached to the ground, and moving?

How do we make reliable measurements of motion occurring over a very wide range of frequencies and amplitudes?

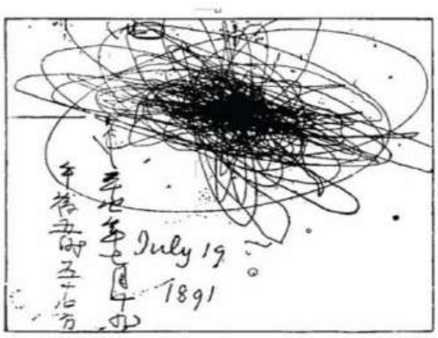
How to record earthquake generated seismic waves

Pendulum seismometer

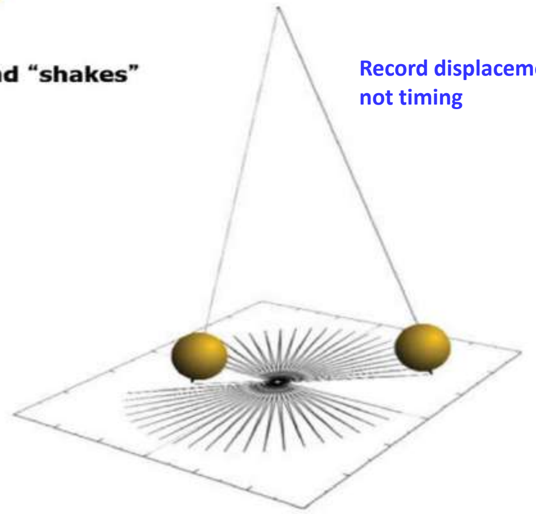
Mass stays still while ground "shakes"

[concept of *inertia*]

Record displacements only, not timing



Earthquake recording



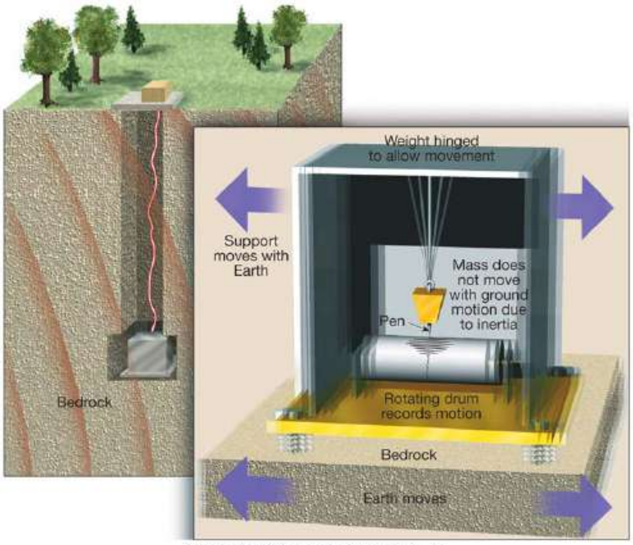
Initial direction of swing is dependent on the direction of the earthquake

How to record earthquake generated seismic waves

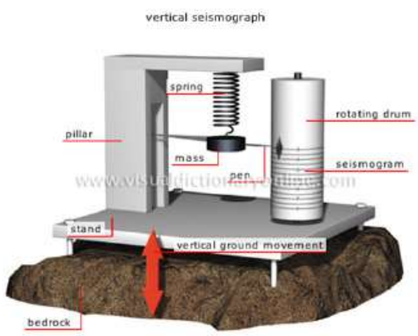
Zhang Heng
(78-139 AD)

Zhang Heng's seismoscope (Model)

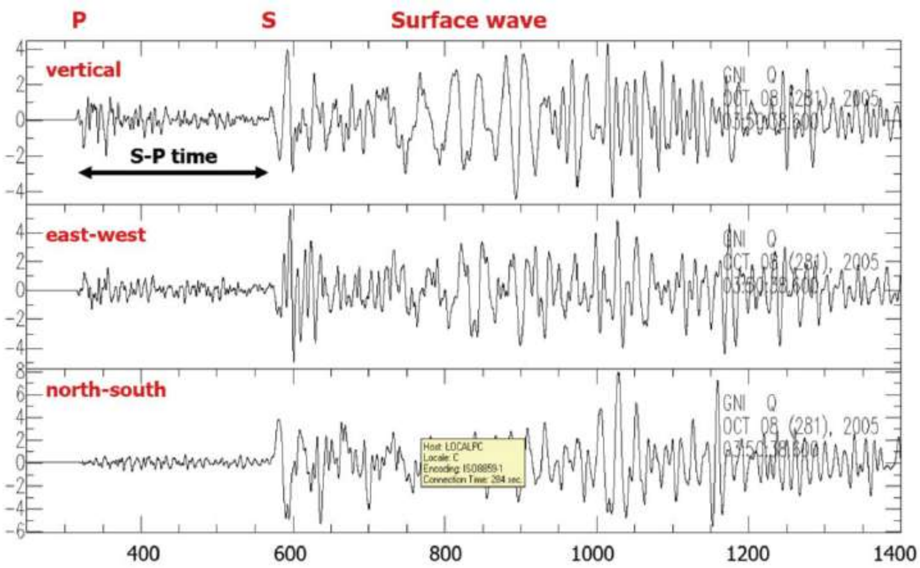
How to record earthquake generated seismic waves



OK. This one only can measures HORIZONTAL ground motions. What about the VERTICAL ones?

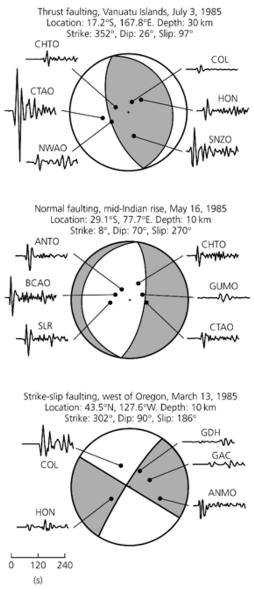


Typical Seismograms



Focal Mechanism - I

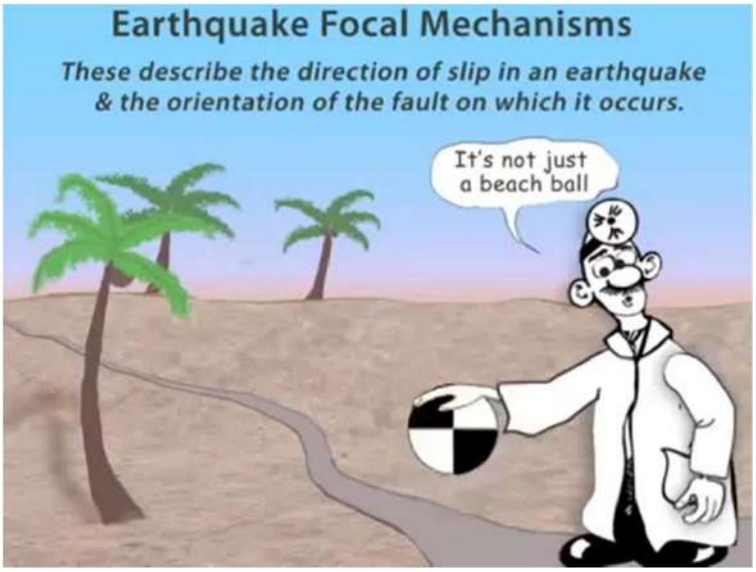
- REVERSE FAULT
- NORMAL FAULT
- STRIKE-SLIP FAULT



Remember, without other information (geological maps, aftershock patterns, geodetic information,...) it is not possible to distinguish the fault and auxiliary planes

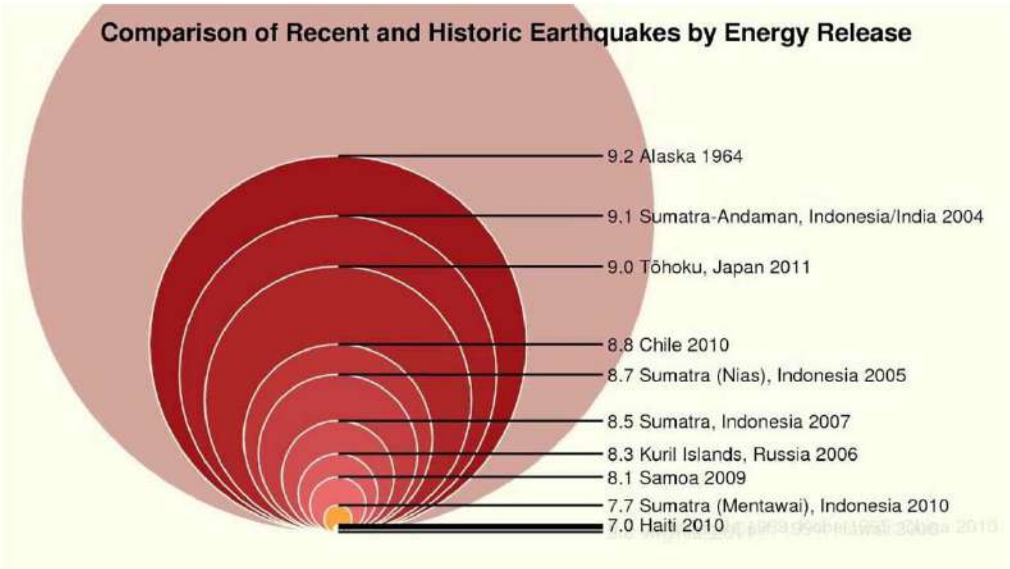
Focal Mechanism - II

- **Summary**



Shall upload the slide separately

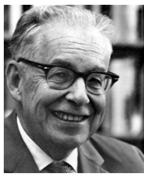
Magnitude of an earthquake



Magnitude of an earthquake

- **Richter Scale**

  A formula based on amplitude of the largest wave recorded on a specific type of seismometer and the distance between the earthquake and the seismometer.



C. F. Richter
(CalTech)

$\mathbf{M_L} = \log_{10}A - \log_{10}A_0(\delta) = \log_{10}[A/A_0(\delta)]$

A: maximum amplitude of seismograph (*Wood-Anderson Seismograph, 100 km distance from epicenter*),
A_0: empirical function of the epicenter distance (δ)

- **Modified Richter Scale**

  Beno Gutenberg modified the scale to include earch quakes of distant (>100 km) locations.

B. Gutengerg
(CalTech)

Magnitude of an earthquake

- **Moment Magnitude Scale**

  The orientation, direction of fault movement and size of an earthquake can be described by the fault geometry and seismic moment. The differing shapes and directions of motion of the waveforms recorded at different distances and azimuths from the earthquake are used to determine the fault geometry, and the wave amplitudes are used to compute moment. The seismic moment is related to fundamental parameters of the faulting process

H. Kanamori
(CalTech)

$\mathbf{M_0} = \mu\, S\, d$

μ: shear strength of the faulted rock; S: affected area of the fault plane; d: average displacement; **UNIT: dyne.cm**

$\mathbf{M_w} = 2/3 \log_{10}(M_o) - 10.7$

The two largest reported moments are 2.5 X 10^{30} dyn·cm (dyne·centimeters) for the 1960 Chile earthquake (M_S 8.5; M_W 9.6) and 7.5 X 10^{29} dyn·cm for the 1964 Alaska earthquake (M_S 8.3; M_W 9.2). M_S approaches it maximum value at a moment between 10^{28} and 10^{29} dyn·cm.

Magnitude of an earthquake

- **Mercalli Intensity Scale**

Measures the released energy by taking into account of surface shaking.

Giuseppe Mercalli
Italy

I. Not felt	Not felt except by a very few under especially favorable conditions.
II. Weak	Felt only by a few persons at rest, especially on upper floors of buildings.
III. Weak	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV. Light	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V. Moderate	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI. Strong	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII. Very Strong	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII. Severe	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX. Violent	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X. Extreme	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
XI. Extreme	Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
XII. Extreme	Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

Next Lecture

VOLCANOES

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 34. Volcanoes

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Experimental Rock Deformation Laboratory

Aims of this lecture

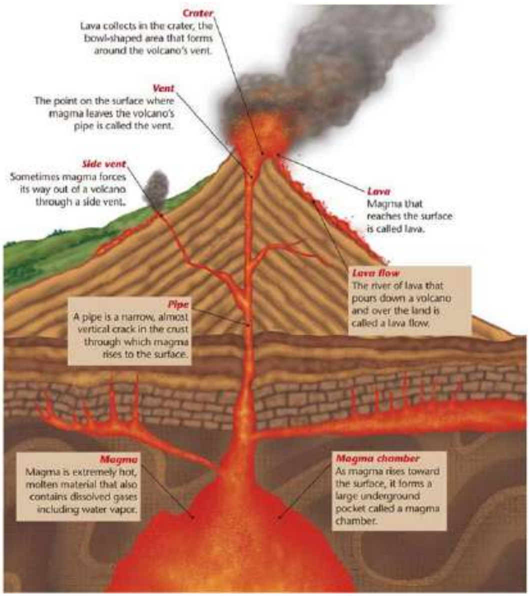
- Volcanoes – definition, eruptive processes
- Types of Volcanoes, Classifications, Lava
- Volcanic Hazards

Reading:
- Marshak's Book (Chapter 9; pages 272-309)
- Grotinger & Jordan's book (Chapter 12)

What is a Volcano?

- A volcano is a vent or 'chimney' that connects molten rock (magma) from within the Earth’s crust to the Earth's surface.
- The volcano includes the surrounding cone of erupted material.

Anatomy of a Volcano



How and why do volcanoes erupt?

- Hot, molten rock (magma) is buoyant (has a lower density than the surrounding rocks) and will rise up through the crust to erupt on the surface.

  Same principle as hot air rising, e.g. how a hot air balloon works

- When magma reaches the surface it depends on how easily it flows (viscosity) and the amount of gas (H_2O, CO_2, S) it has in it as to how it erupts.
- Large amounts of gas and a high viscosity (sticky) magma will form an explosive eruption!

  Think about shaking a carbonated drink and then releasing the cap.

- Small amounts of gas and (or) low viscosity (runny) magma will form an effusive eruption

  Where the magma just trickles out of the volcano (lava flow).

Volcanoes and Earth System

- **How do volcanoes affect Earth's spheres?**
  - Origin of atmosphere and oceans via outgassing
  - Mass extinctions

    K-T boundary – 65 million years ago – demise of the dinosaurs (Volcanism and/or asteroid?)
- **How do volcanoes affect climate?**
  - Gases and particles

    Tambora 1815 – followed by "year without a summer"

    Pinatubo, 1991: sulfuric acid formed aerosols; cooled temperatures in some areas by as much 0.5 degrees C
  - Volcanoes emit CO_2

The scream

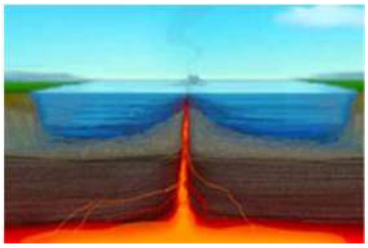
The Scream (1893) - Edvard Munch

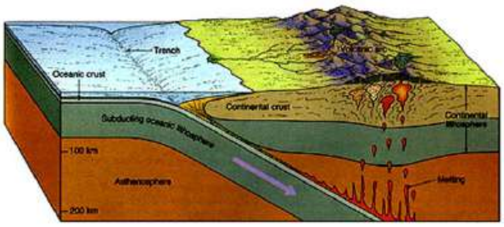
Painted in 1893 based on Munch's memory of the brilliant sunsets following the 1883 Krakatoa eruption.

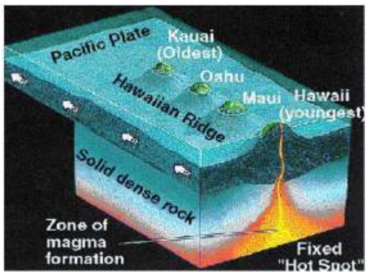
"I was walking along the road with two friends – the sun was setting – suddenly the sky turned blood red – I paused, feeling exhausted, and leaned on the fence – there was blood and tongues of fire above the blue-black fjord and the city – my friends walked on, and I stood there trembling with anxiety – and I sensed an infinite scream passing through nature.."

Where do the volcanoes occur?

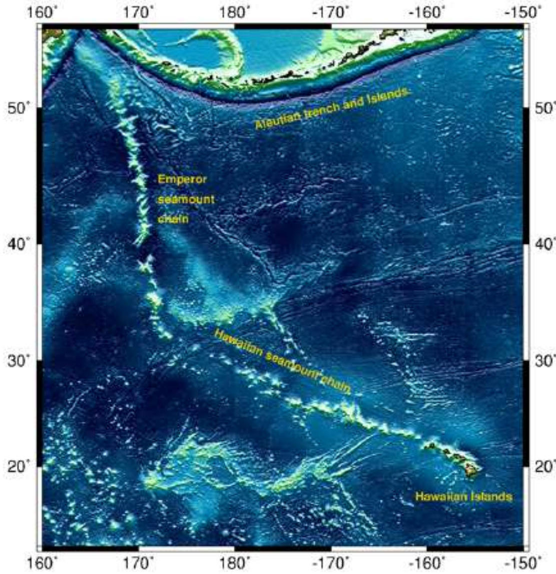
- Volcanoes occur at both divergent and convergent boundaries and also at hot spots.

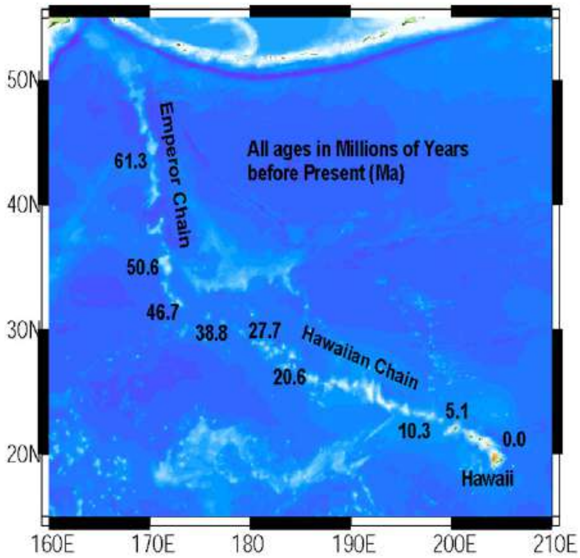




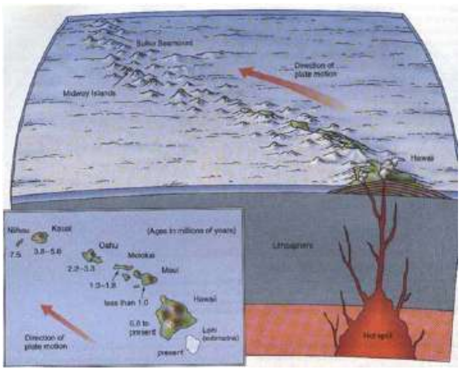


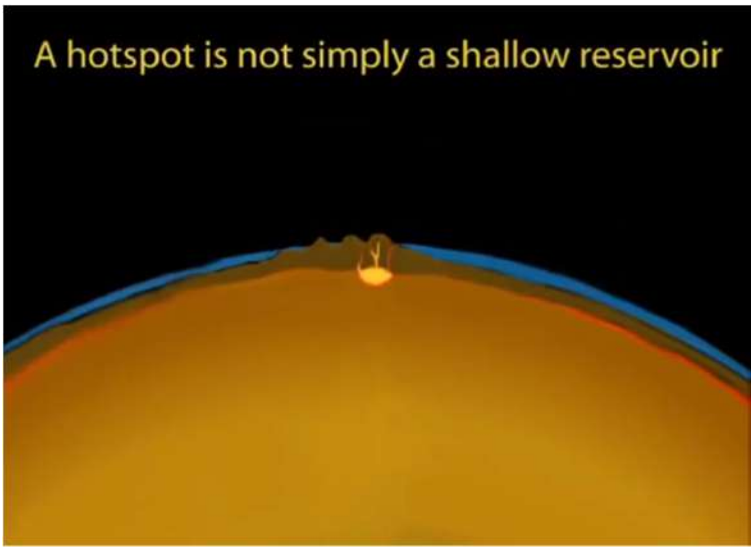
Volcanoes and plate tectonics





Volcanoes and Plate Tectonics





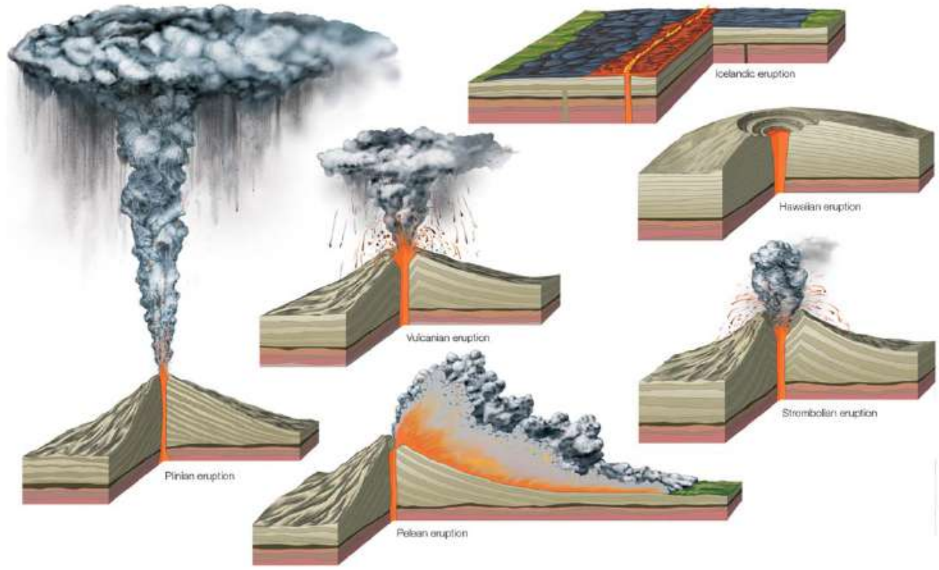
Volcanoes at divergent plate boundaries

- At a divergent boundary, the lithosphere becomes thinner as two plates pull away from each other.
- A set of deep cracks form in an area called a *rift zone*.
- Hot mantle rock rises to fill these cracks. As the rock rises, a decrease in pressure causes hot mantle rock to melt and form magma.
- The **magma** that reaches Earth's surface is called **lava**.
- Basaltic magma rises to Earth's surface through these fissures and erupts non-explosively

Types of Volcanoes

- Shield Volcanoes
- Flood Basalts
- Scoria Cones
- Lava Domes
- Calderas
- Stratovolcanoes

Types of Eruptions



Why do we have different types of volcanos?

- The process of magma formation is different at each type of plate boundary.
- Therefore, the composition of magma differs in each tectonic setting.
- Tectonic settings determine the types of volcanoes that form and the types of eruptions that take place.

Shield Volcanoes

Shield volcanoes form when repeated eruptions from the same magma conduit system build piles of overlapping lava flows. Profiles are upwardly convex.

- Low viscosity
- Low Volatiles
- Produce large volume from lava
- flows
- Basaltic
- Shallow slopes

Shield Volcanoes

Flood Basalts

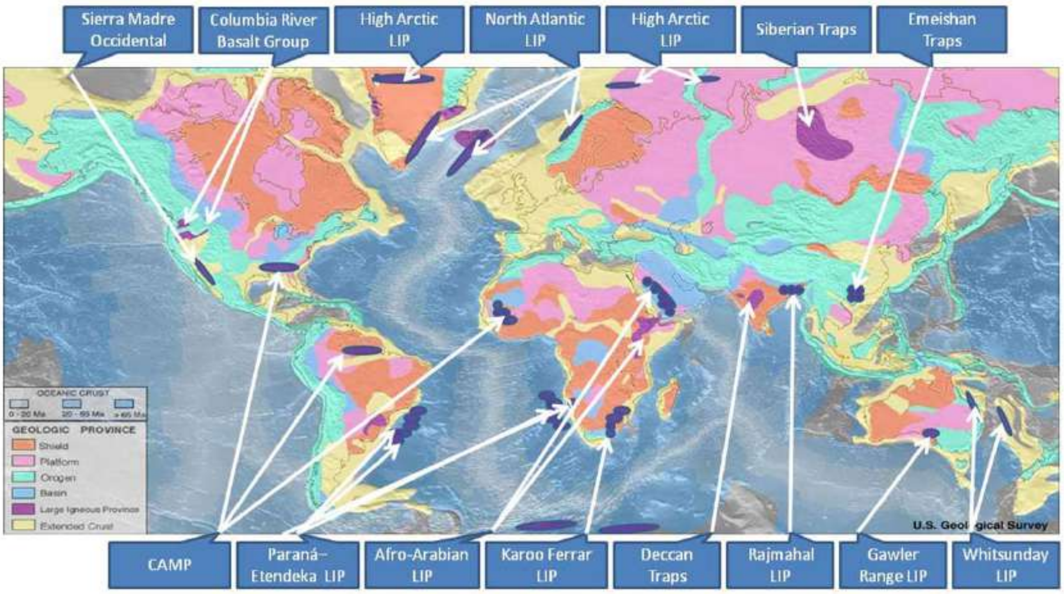
Some parts of the world are covered by thousands of square kilometers of thick basalt lava flows - individual flows may be more than 50 meters thick, and individual flows extend for hundreds of kilometers.

- Largest volcanic events on Earth.
- Erupt extremely large amounts of magma in a relatively short time of 1 million years.
- Occur on all continents and on all ocean floors, but none has occurred in historic time.
- Although lava flows are the main hazard, the large amount of CO2 and SO2 released is able to modify our climate.


Deccan Trap, India


Columbia River Flood Basalt, USA

Flood Basalts



Scoria / Cinder Cones

Produced during a single eruptive event (usually Strombolian eruptions), lasting a few hours to several years

- Conical Hills, Low Height, large crater
- Basaltic-Andesitic
- Explosive
- Once activity ceases usually never active again

N. Arizona, USA

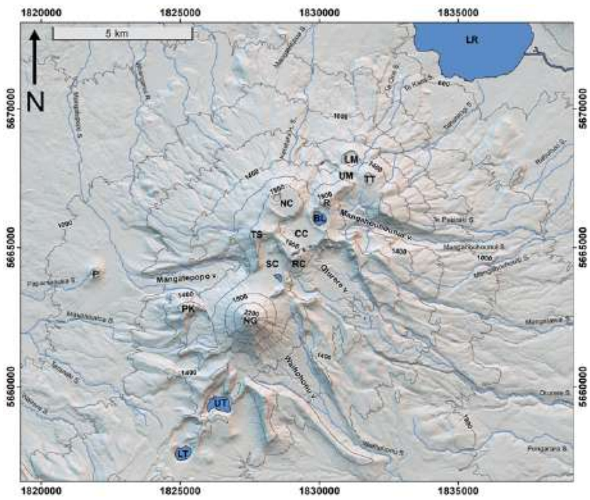
Stratovolvanoes

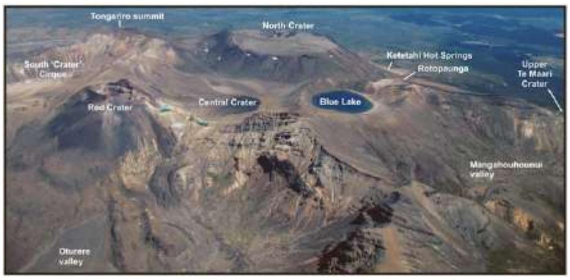
- Steep-sided, symmetrical peaks
- Built of alternating layers of pyroclastic deposits and capped by andesitic-rhyolitic lava flows
- Eruption styles vary from Vulcanian-Plinian
- Highly viscous lavas, Usually explosive eruptions
- Comprise 60% of the Earth's volcanoes
- Produce pyroclastic flows, lahars, ash plumes and lava flows

Mt. Fuji, Japan

Mt. Taranaki, NZ

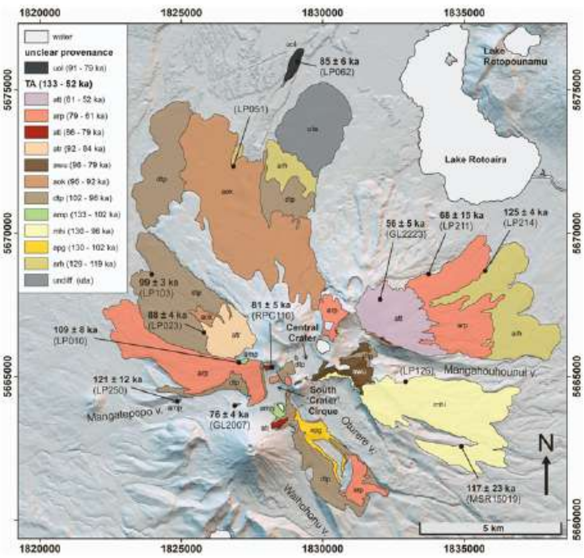
Stratovolvanoes

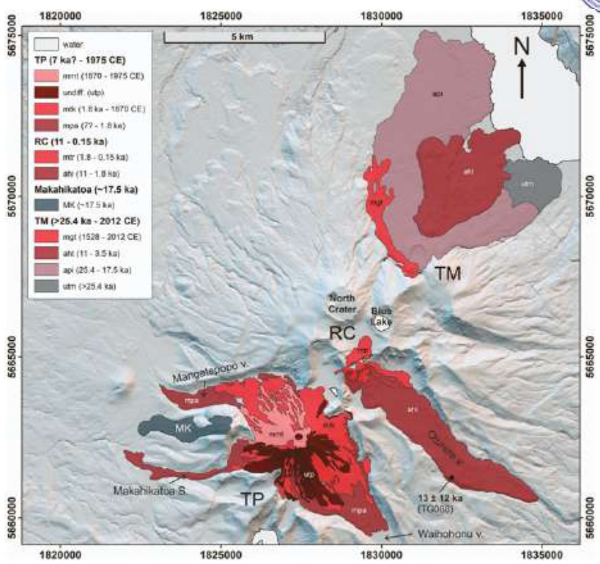




Pure et al., 2020

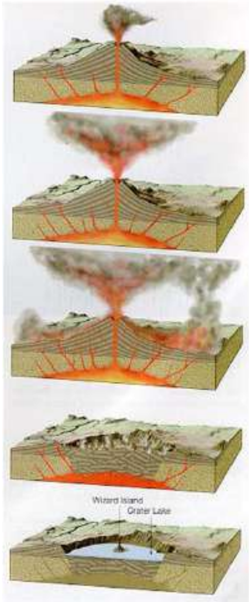
Stratovolvanoes





Pure et al., 2020

Calderas



- Caldera-forming eruptions are the largest of the violent, explosive volcanoes
- Large volcanic depressions formed by roof collapse into partially erupted magma chambers
- Calderas range from 2-75 km in diameter and are formed by inward collapse
- Collapse occurs following large Plinian eruptions producing pyroclasts. Void spaces are left causing the mountain to collapse into the magma chamber
- Three different Caldera settings:
    - Calderas in the summit of shield cones (Mauna Loa)
    - Summit of stratovolcanoes (Crater Lake Oregon)
    - Giant continental calderas (Yellowstone)

Calderas

Caldera Erta, Ethiopia

Kaguyak volcano, Alaska

Types of Lavas

Aa:	lava that is thick and sharp
Pahoehoe:	lava that forms thin crust and wrinkles
Pillow lava:	lava that erupts under water, has a round shape
Blocky lava:	cooler, lava that does not travel far from eruption, jagged when it dries.

Aa

Aa: lava that is thick and sharp

Pahoehoe

Pahoehoe: lava that forms thin crust and wrinkles

Pillow Lava

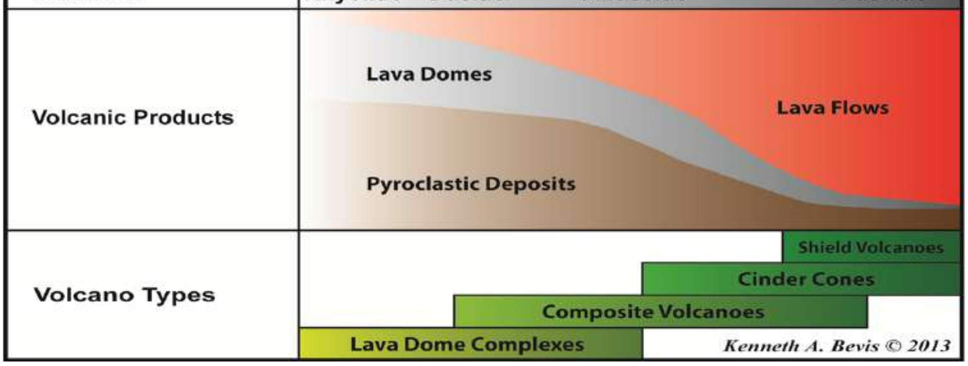
Pillow lava: lava that erupts under water, has a round shape

Blocky Lava

Blocky lava: cooler, lava that does not travel far from eruption, jagged when it dries.

Magma composition and flow properties

Magma Composition	Felsic	Intermediate	Mafic
Silica Content	70%	60%	50%
Water (Gas) Content	5.0%	2.0%	0.5%
Eruption Temperature	750-900 °C	900-1000 °C	1100-1200 °C
Viscosity	Higher	Intermediate	Lower
Explosiveness	More Explosive		More Effusive
Volcanism	Rhyolitic Dacitic	Andesitic	Basaltic



Explosive eruptions

- Explosive volcanic eruptions can be catastrophic Erupt 10's-1000's km^3 of magma
- Send ash clouds >25 km into the stratosphere
- Have severe environmental and climatic effects
- Hazardous!!!
- Three products

    Ash Fall

    Pyroclastic Flow (more particles)

    Pyroclastic surge (more gas)

Large eruption column and ash cloud from an explosive eruption at Mt Redoubt, Alaska

Pyroclastic Flow and surge

A truck carrying volcanologists and a film crew attempting to out run a pyroclastic flow in Indonesia

Effusive Eruptions

- Effusive eruptions are characterized by outpourings of lava on to the ground.
- This happens either because there is not enough gas (volatiles) in the magma to break it apart upon escaping, or the magma is too viscous (sticky) to allow the volatiles to escape quickly.
- Lava flows generated by effusive eruptions vary in shape, thickness, length, and width depending on the type of lava erupted, discharge rate (how fast it comes out of the vent), slope of the ground over which the lava travels, and duration of eruption.
- Although not generally as hazardous as explosive eruptions, lava flows can burn and bury buildings and forests and do pose a danger to people living on or near an active volcano.

Volcanic Fatalities

- 92,000 Tambora, Indonesia 1815
- 36,000 Krakatau, Indonesia 1883
- 29,000 Mt Pelee, Martinique 1902
- 15,000 Mt Unzen, Japan 1792

But, volcanoes cause fewer fatalities than earthquakes, hurricanes and famine.

Volcanic soil is very fertile and rich in minerals so people move on to the sides of volcanoes to plant crops. This puts them in great danger if there is an eruption.

Volcanic Fatalities

Volcanic Hazards

- Pyroclastic flow
- Lahars/Mud flows
- Pyroclastic fall
- Lava flow
- Noxious Gas
- Earthquakes

Pyroclastic Flow- POMPEII

On August 24, 79AD Mount Vesuvius literally blew its top, erupting tones of molten ash, pumice and sulfuric gas miles into the atmosphere. Pyroclastic flows flowed over the city of Pompeii and surrounding areas.

Lahar / Mud Flow

- Hot volcanic activity can melt snow and ice
- Melt water picks up rock and debris
- Forms fast flowing, high energy torrents
- Destroys all in its path

Pyroclastic Fall

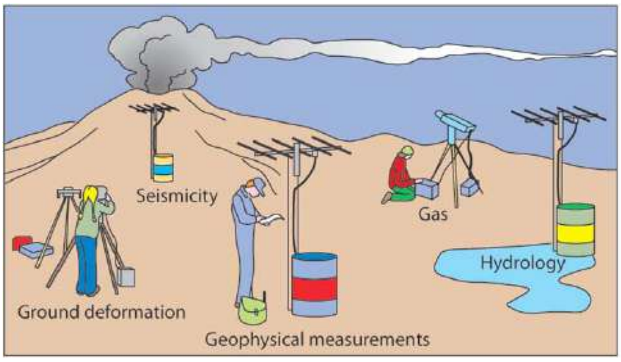
- Ash Load
- Collapses roofs
- Brings down power lines
- Kills plants
- Contaminates water supplies
- Respiratory hazard for humans and animals

Lava Flow

- Lava flows although generally slower moving and less catastrophic than pyroclastic flows still remain dangerous.
- Lava flows have temperatures in excess of 200 degrees Celsius. Therefore will burn any flamable material it contacts with.
- Thick lava flows will bury all in it's path including infrastructure (buildings, roads, waterways etc.) and agricultural land.

Volcano Monitoring

Volcano Observatories are set up on all active volcanoes that threaten the human population. These are designed to monitor and potentially to predict the eruptive behaviour of the volcano in question.



- Increased earthquakes in the area (increased seismicity)
- Swelling and cracking of the ground (deformation)
- Change in the amount of or chemistry of the gas coming out of the volcano
- Change in the groundwater levels or chemistry.

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 35. Climate System

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Components of Climate System

Reading:
- Grotinger & Jordan's book (Chapter 15)

The Climate and Weather

- **WEATHER**: Short term changes (minutes to weeks) in the Atmosphere

  Combination of temperature, humidity, precipitation, cloudiness, visibility, and wind

- **CLIMATE**: Long term (approximately 30 years or more) changes in the Atmosphere

  Climate to look for trends or cycles of variability, such as the changes in wind patterns, ocean surface temperatures and precipitation over the Gangetic Planes or Bay of Bengal or other phenomena into the bigger picture of possible longer term or more permanent climate changes.

The Climate and Weather

- **Are weather and climate treated separately?**

  Technically, NO, particularly in the context of weather forecasting and climate predictions.

  What will the temperature be tomorrow? Will it rain? How much rain will we have? Will there be thunderstorms? Etc. are common weather forecasters' questions.

  The weather forecasts are based on numerical models (often ML is used) with the measured input data (air pressure, temperature, humidity and winds).

  The accuracy of weather forecasts depends on both the model and on the forecaster's skill. Short-term weather forecasts are accurate for up to a week.

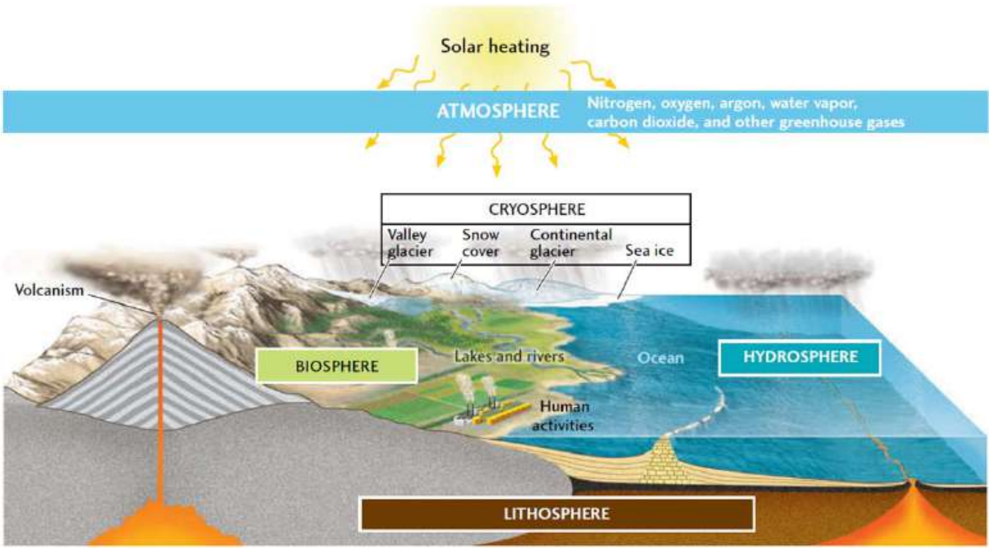
  Climate predictions try to answer questions like are we facing global warming? How much will sea level rise?

  Climate predictions are made using global climate models. Unlike weather forecast models, climate models cannot use observations because there are no observations in the future. But experience from the PAST.

The components of the Climate

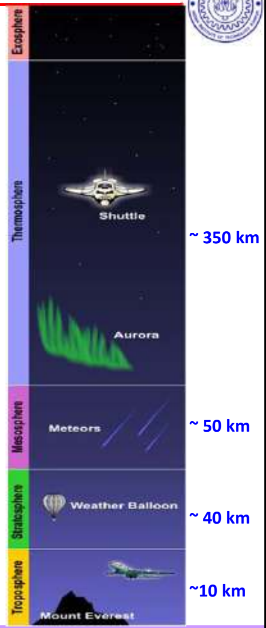
- **Earth System**
  - Atmosphere
    - Exosphere
    - Thermosphere
    - Mesosphere
    - Stratosphere
    - Troposphere
  - Hydrosphere
    - Sea water
    - Terrestrial Water
  - Biosphere
  - Lithosphere
    - Crust
    - Upper Mantle
  - Anthroposphere

The components of the Climate



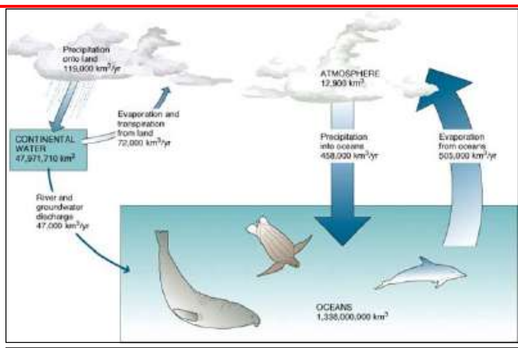
The Atmosphere

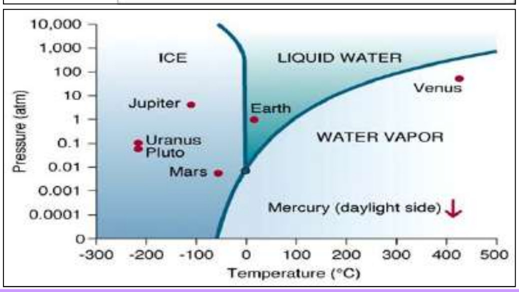
- The earth's atmosphere is a very thin layer wrapped around a very large planet
- Two gases make up the bulk of the earth's atmosphere: nitrogen (78% of the atmosphere), and oxygen (21%). Various trace gases make up the remainder.
- Based on temperature, the atmosphere is divided into four layers: the **troposphere**, **stratosphere**, **mesosphere**, and **thermosphere**. The outermost layer is exosphere.
- Energy is transferred between the earth's surface and the atmosphere via conduction, convection, and radiation.
- Ocean currents (and winds, too) play a significant role in transferring this heat poleward. Major currents, such as the northward flowing Gulf Stream, transport tremendous amounts of heat poleward and contribute to the development of many types of weather phenomena.



The Hydrosphere

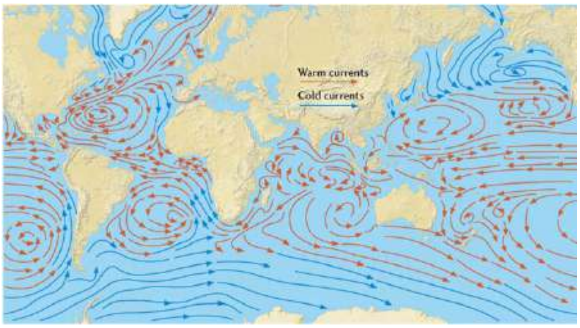
- Earth- the only watery planet! The BLUE planet.
- All forms of H_2O: water, ice (cryosphere), water-vapour (atmosphere).
- Responsible for many of the landform and surface features on continents.
- Without surface water, there would be no rivers, valleys, glaciers etc.
- 33 million cubic km of ice (cryosphere), primarily in the ice caps of the polar regions, seasonal exchange of which with water in important in climate system.



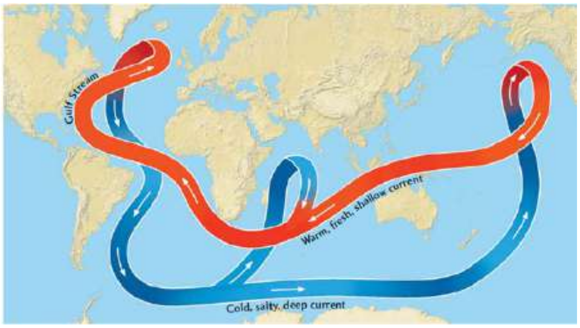


The Hydrosphere

- water circulation is slower in the oceans than air in the atmosphere. As water can store much more heat energy, the ocean currents transport heat energy very effectively and give rise to large-scale circulation patterns within ocean basins (both vertically and horizontally due to temperature and salinity gradients).



Currents at the surface of the oceans are generated by winds



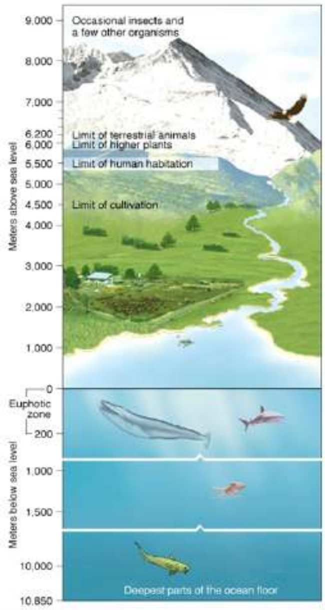
Conveyer belt like Ocean water circulation

The Hydrosphere

A movie from NASA and the satellite Aquarius

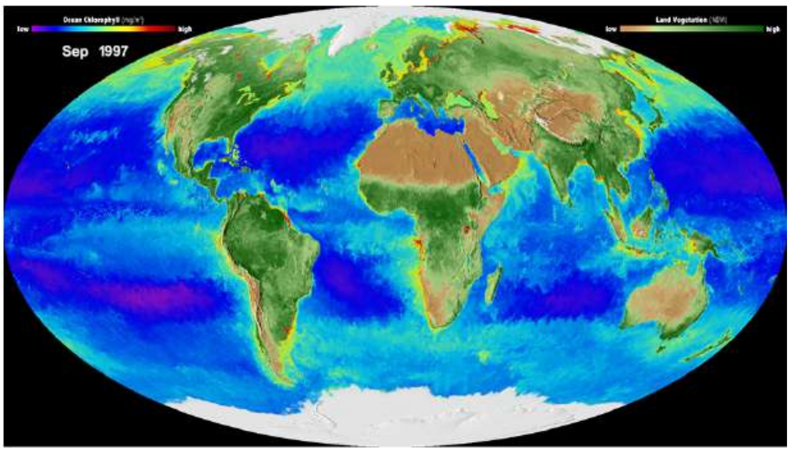
The Biosphere

- Considers the living world - microbes, plants, and animals. Age- 3.5 billion years.
- The biosphere extends to any place that life of any kind might exist. The biosphere extends to the upper areas of the atmosphere where birds and insects can be found. It also reaches to dark caves deep in the ground or to the bottom of the ocean at hydrothermal vents.
- Factors, that control the existence and diversity of the Biosphere
  - Big factors: distance from sun, tilt of earth, seasonal variation
  - Small factors: climate, daily weather, erosion, earthquake
  - Micro-factors: chemical erosion, oxidation, reduction.
  - What about US! Are we also a factor to biosphere?



The Biosphere

Global change of biosphere (last 20 years) - NASA



In the ocean, dark blue to violet represents warmer areas where there is little life due to lack of nutrients, and greens and reds represent cooler nutrient-rich areas. The nutrient-rich areas include coastal regions where cold water rises from the sea floor bringing nutrients along and areas at the mouths of rivers where the rivers have brought nutrients into the ocean from the land.

On land, green represents areas of abundant plant life, such as forests and grasslands, while tan and white represent areas where plant life is sparse or non-existent.

The Lithosphere

- Mostly land-surface of the earth, which can absorb and desorb the Solar Energy (and Earth's internal heat)
- Atmosphere is also heated by the surface of the Earth, and most of the time in uneven manner (albedo)
- One of the major sources of Water
- Change of wind directions due to topography, temperature gradient

PDF TOOLS SHARE

DEVELOPMENTS IN EXPLORING LITHOSPHERE AND ATMOSPHERE[1]

H. LANDSBERG

Institute of Meteorology, University of Chicago, Chicago, Illinois

In earth science the greatest advantures were those concerned with the exploration of the surface of our planet. The centuries between the fifteenth and the nineteenth are packed with the

Feedback Loops

Positive feedbacks tend to amplify changes in a system, whereas **negative feedbacks** tend to stabilize the system against change.

Water vapor feedback:

Radiative damping:

Plant growth feedback:

Albedo feedback:

Grotinger & Jordan's book (page 415)

Next Lecture

Atmosphere

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 36. Atmosphere

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Experimental Rock Deformation Laboratory

IITK

Aims of this lecture

- Early Atmosphere
- Present Atmosphere, composition and layers

Reading:
- Grotinger & Jordan's book (Chapter 15)

The Atmosphere

- The gaseous envelope that surrounds a planet and/or other celestial body
- AIR: Mixture of gasses and suspended particles that surrounds Earth
- The composition of Atmosphere is important as

  (1) we breath it;
  (2) maintains Earth's surface temperature; control the weather and overall climate.
  (3) ozone to protect from UV

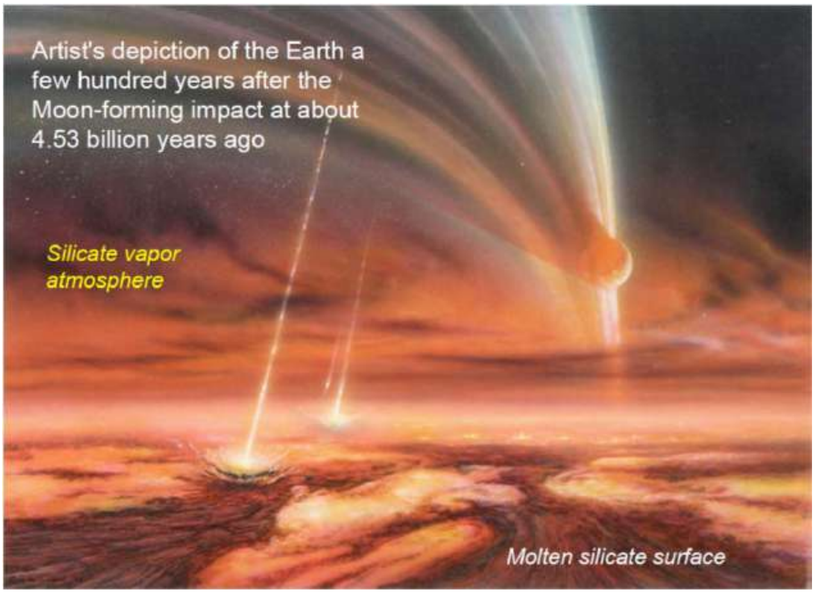
The Aerosols

- There are also aerosols in the atmosphere
- Tiny droplets or solid particles, so small to remain suspended in the air

  Smoke
  Sea-salt crystals
  Ice-crystals
  Dust
  Volcanic emissions
  Industrial pollution

- Some aerosols (soot) absorb solar radiation: heating
- Some aerosols (sulfur) reflect incoming radiation: cooling
- Some aerosols form clouds..

The surface of the Earth since it's birth



- Molten surface, very hot, silicate rain !
- The carbons also left by degassing and the concentration of carbon in the atmosphere was very high !
- The greenhouse effect was enormous.
- What brought back the carbons inside the Earth again? When?

The early Atmosphere

- Earth's first atmosphere was most likely comprised of hydrogen and helium (two most abundant gases found in the universe!)
- Through the process of *outgassing*, the outpouring of gases from the earth's interior, many other gases were injected into the atmosphere -
  - Water vapour
  - Carbon dioxide
  - Nitrogen
  - Oxygen (not a product of degassing !)
- As outgassing occurred over a period of millions of years, the atmosphere evolved to its current state

The Contributions from Volcanoes

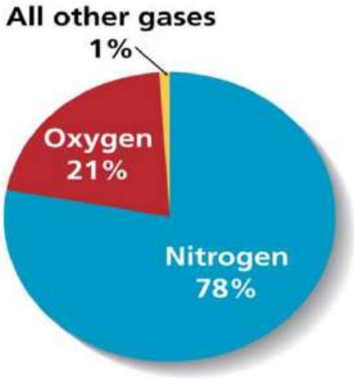
GNS Science, NZ

The Contributions from Volcanoes

Volcano Tectonic Style Temperature	**Kilauea Summit** Hot Spot 1170°C	**Erta` Ale** Divergent Plate 1130°C	**Momotombo** Convergent Plate 820°C
Water Vapor H_2O	37.1	77.2	97.1
Carbon Dioxide CO_2	48.9	11.3	1.44
Sulfur Dioxide SO_2	11.8	8.34	0.50
Hydrogen H_2	0.49	1.39	0.70
Carbon Monooxide CO	1.51	0.44	0.01
Hydrogen Sulfide H_2S	0.04	0.68	0.23
Hydrochloric Acid HCl	0.08	0.42	2.89
Hydrofluoric Acid HF	---	---	0.26

Examples of volcanic gas compositions, in volume percent concentrations (from Symonds et. al., 1994)

The Contributions from Volcanoes



Gas	Percentage by Volume
Nitrogen (N_2)	78.084
Oxygen (O_2)	20.946
Argon (Ar)	0.934
Carbon dioxide (CO_2)	0.037
Neon (Ne)	0.00182
Helium (He)	0.00052
Methane (CH_4)	0.00015
Krypton (Kr)	0.00011

Less, but also important

What happened with all CO_2 and H_2O that come from volcanoes?

Fate of Volcano generated water

Atmosphere cannot hold all water vapour injected from volcanoes

The water vapour condensed into clouds and over time formed the oceans

If we consider the volume, it would be a very small ball in front of the total mass of the earth.

Reservoir	Volume (million Km3)	Percent of Total	Reproduction Rate Cu.Km/ year
Oceans & Seas	1370	96.5	452
Ice caps & Glaciers	24	1.74	3
Ground water	60	1.74	12
Rivers, Lakes & Swamp	0.2812	0.0132	39
Soil moisture	0.083	0.001	83
Water vapour	0.014	0.001	525
Biosphere	0.0011	0.0001	39
Total	1454.3793	99.9953	1153

HH Lamb, 1972

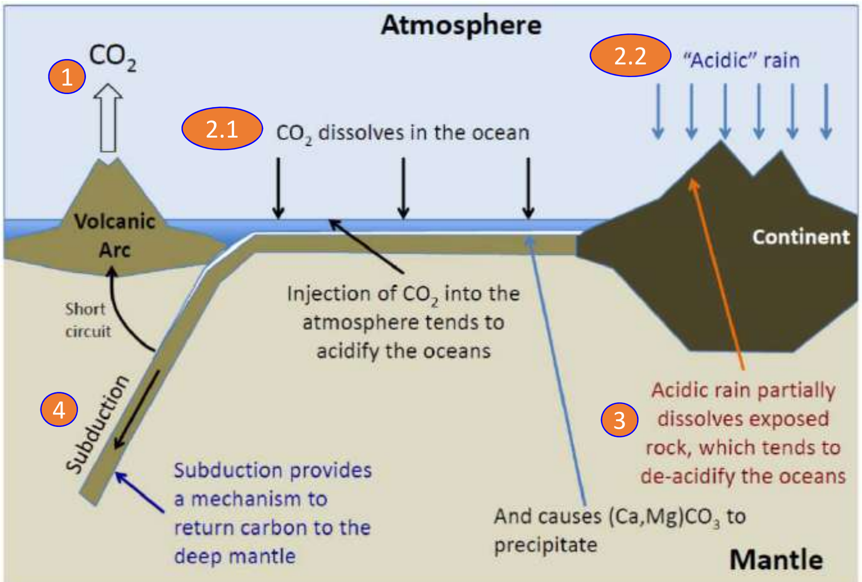
Fate of Volcano generated CO_2

CO2 is removed from the atmosphere by
- Biosphere
- Dissolution in oceans
- Chemical weathering
- Tectonic processes
- Into the rocks

	Relative units
Biosphere	**2**
Atmosphere (as CO_2)	**70**
Oceans (as dissolved CO_2)	**4000**
Fossil Fuels	**800**
Shales	**800,000**
Carbonate Rocks	**2,000,000**

PK weys, 197o

Climate-regulating carbon cycle



Source of Nitrogen, Argon and Oxygen

Very small amount injected from volcanoes, but nitrogen is almost chemically inert and also not soluble in sea water

Nitrogen stays in the atmosphere and there is almost no removal

Radioactive decay in the rocks

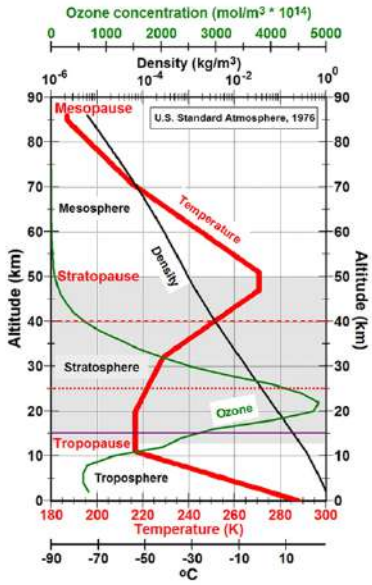
Similar process of nitrogen

Photosynthesis

Now the O2 concentration is about 20% and it was maximum (~35%) 550 myr ago.

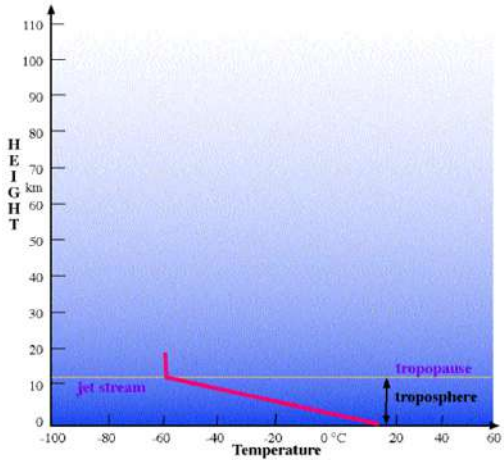
The Atmosphere

The atmosphere is comprised of layers based on temperature. These layers are the troposphere, stratosphere, mesosphere and thermosphere. A further region at about 500 km above the Earth's surface is called the exosphere.



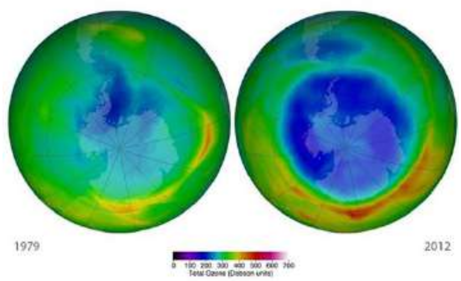
The Troposphere

- Temperature decreases with height (lapse rate: 6.5 °C/km).
- Extends from surface to about 10-12 km (increases in summer).
- The height of the troposphere varies from the equator to the poles. At the equator it is around 11-12 miles (18-20 km) high, at 50°N and 50°S, 5½ miles and at the poles just under four miles high.
- top of troposphere is called the tropopause that separates troposphere from stratosphere.
- Very unstable, where all the weather occurs.

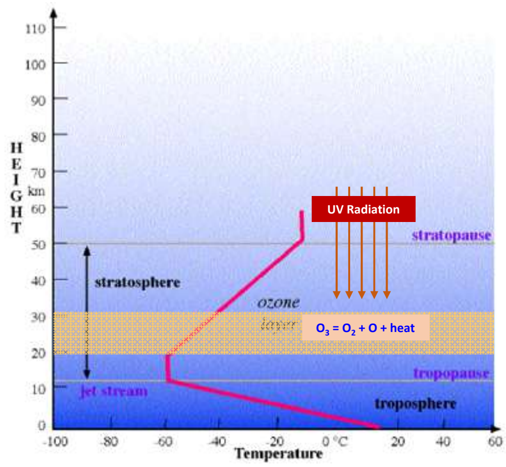


The Stratosphere

- Temperature increases with height (inversion layer). WHY?
- Extends from the tropopause to about 40-50 km
- Holds about 19% of the atmospheric gases; but almost no water vapour.
- Contains the ozone layer (20-30 km).

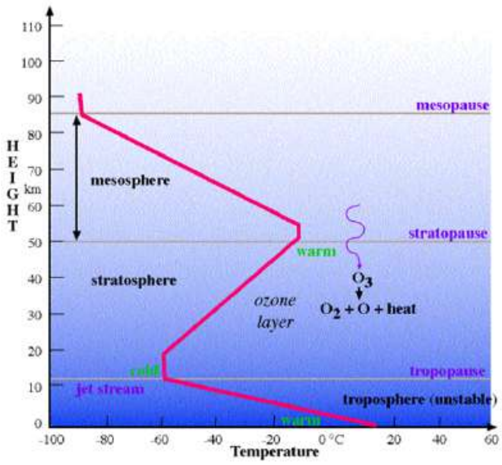


1 Dobson unit : a layer of gas of 10 μm thick at constant PT. Image source: NASA



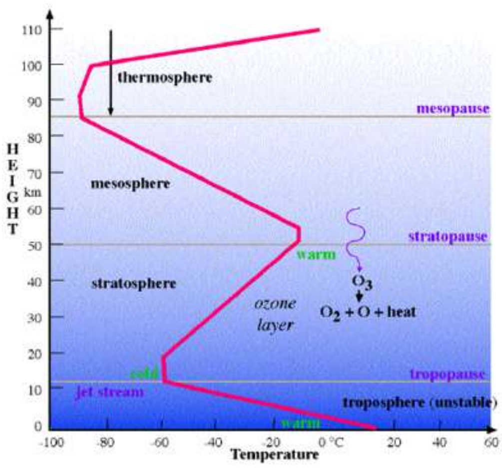
The Mesosphere

- Temperature decreases with height.
- Extends from the stratosphere to about 40-50 km
- The gases, including the oxygen molecules, continue to become thinner and thinner with height.
- the gases in the mesosphere are thick enough to slow down meteorites hurtling into the atmosphere, where they burn up, leaving fiery trails in the night sky.
- the mesopause is the coolest layer in the atmosphere.



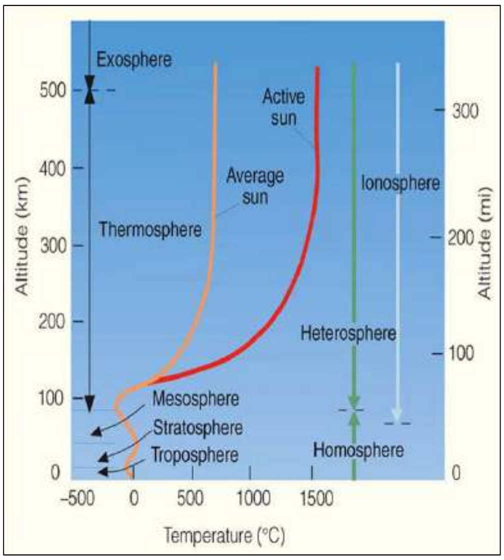
The Thermosphere

- Temperature increases with height (reaches about 2000 °C).
- Extends from the mesosphere to about 350 km
- The gases of the thermosphere are increasingly thinner than in the mesosphere. Only the higher energy ultraviolet and x-ray radiation from the sun is absorbed.

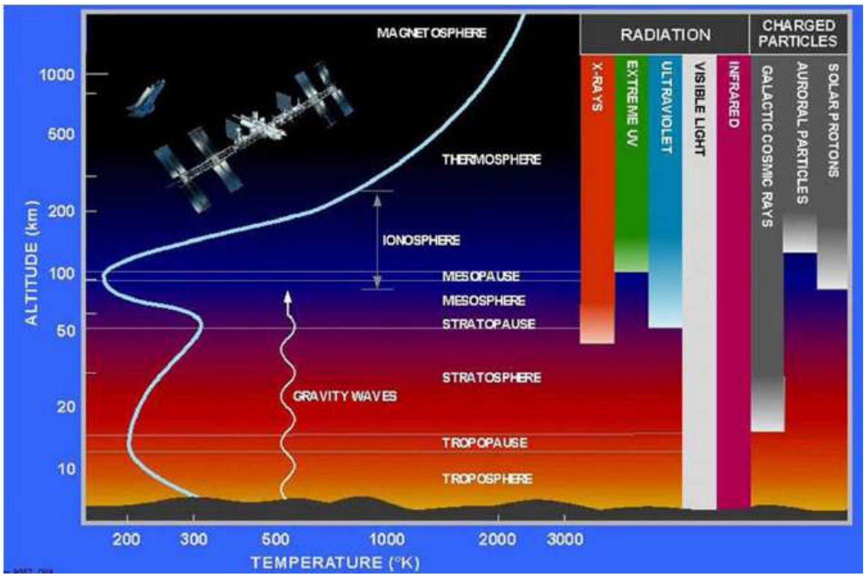


The Ionosphere

- An electrified region within the upper atmosphere.
- contains large concentrations of ions (charged particles) and free electrons.
- The ionosphere is important for radio wave propagation.



Stratification & anatomy of atmosphere



Additional readings

Short- and Long-term variations of climate (Regional and Global)

Pages 417-423; Grotinger & Jordan's book

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ES0213A: Fundamentals of Earth Sciences

Lecture 37. Landforms

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Experimental Rock Deformation Laboratory

Aims of this lecture

Categories of various Landforms and their driving forces

Aeolian Landform*

Fluvial Landform*

Glacial Landforms

Readings:
Grotinger & Jordan's Book: Chapters 18-21

Surface-forms

A number of surface-forms we see on the Earth, both in lands and oceans, rivers and lakes – they are beautiful, mesmerizing, thought-provoking and sometimes, scary..

All such surface form do develop naturally and slowly; sometime fast (during hazards) and also man-made


Photo: Santanu Misra


Photo: Santanu Misra

GEOMORPHOLOGY: A discourse of Earth's surface forms

Earth's surface

The surface of the earth is not flat.. WHY?

Was is flat before and now developing more intense topography?

Was is extremely rugged before and now becoming flat?

a variety of geologic processes can cause one portion of the surface to move up or down relative to an adjacent region. We refer to the relative upward movement of a region as **uplift** and the relative downward movement of a region as **subsidence**.

The continuous uplift and subsidence contributes to develop and maintain the **dynamic topography** of the earth's surface

UPLIFT and SUBSIDENCE

• **Thickening of the crust.** At convergent and collisional boundaries, compression causes the crust to shorten horizontally (by development of folds, faults, and foliations) and thicken in the vertical direction.
Intrusion or extrusion of igneous rocks thickens the crust or builds volcanoes on top of the surface, and also can cause uplift.

• **Heating of the lithosphere.** Heating decreases the thickness and density of lithosphere, so to maintain isostatic equilibrium, lithosphere floats higher.

• **Rebound due to unloading.** Removal of a heavy load (such as a glacier or mountain) from the surface causes the Earth's surface to rise in a manner similar to the way a trampoline's surface rises when you step off it.

• **Delamination.** If dense lithospheric mantle separates from the base of the plate and sinks into the mantle, the surface of the lithosphere rises. The effect resembles the consequence of unloading ballast from a ship.

UPLIFT and SUBSIDENCE

• **Thinning of the crust due to stretching.** In rifts, where the crust undergoes horizontal stretching, the axis of the rift drops down by slip on normal faults.

• **Cooling of the lithosphere.** Cooling thickens the lithospheric mantle and makes it denser, so to maintain isostatic equilibrium, the lithosphere sinks down and its surface lies at a lower elevation.

• **Sinking due to loading.** Where a heavy load (such as a glacier or volcano) forms on the Earth's surface, the lithosphere warps downward, somewhat like the surface of a trampoline warps down when you stand on it.

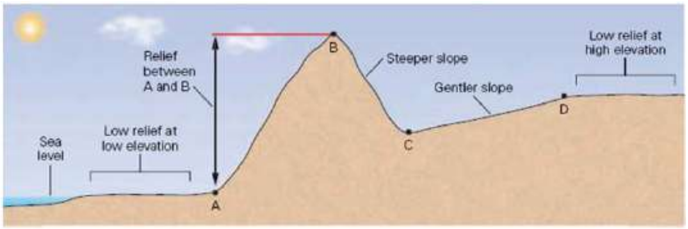
• **Erosion.** Driven by natural agents like water, wind and ice.

Controlling Factors: Erosion

Eroding or transporting agents: Water (Fluvial), ice (Glacial), and wind (Aeolian) all cause erosion and transport sediment. But the shapes of landforms produced by each are different because of differences in the abilities of these agents to carve into the substrate and to carry debris. Of these three, water has the greatest impact, on a global basis.

Controlling Factors: Relief, Steepness, cohesion

Relief: The elevation difference, or relief, between adjacent places in a landscape determines the height and steepness of slopes. Steepness, in turn, controls the velocity of ice or water flow and determines whether rock or soil stays in place or tumbles downslope.



Mountains have high relief

Planes have low relief

Floodplains are cohesive

Deserts are non-cohesive

Controlling Factors: Climate, Weather, Materials

Climate & Weather: The average mean temperature, the volume of precipitation, and the distribution of precipitation through the year (in other words, the *climate*), determines whether running water, flowing ice, or wind serves as the main agent of erosion or deposition in a region. Climate also affects the way in which substrate weathers.

Substrate composition: The material comprising the substrate determines how the substrate responds to erosion. For example, strong rocks can stand up to form steep cliffs, while soft sediment collapses to generate gentle slopes.

Controlling Factors: Life and Time

Life activity: Some life activity weakens the substrate (by burrowing, wedging, or digesting), while some holds it together (by binding it with roots).

Time: Landscapes evolve through time, in response to continued erosion and/or deposition. For instance, a gully that has just started to form in response to the flow of a stream does not look the same as a deep canyon that develops after the same stream has existed for a long time.

AEOLIAN LANDFORMS

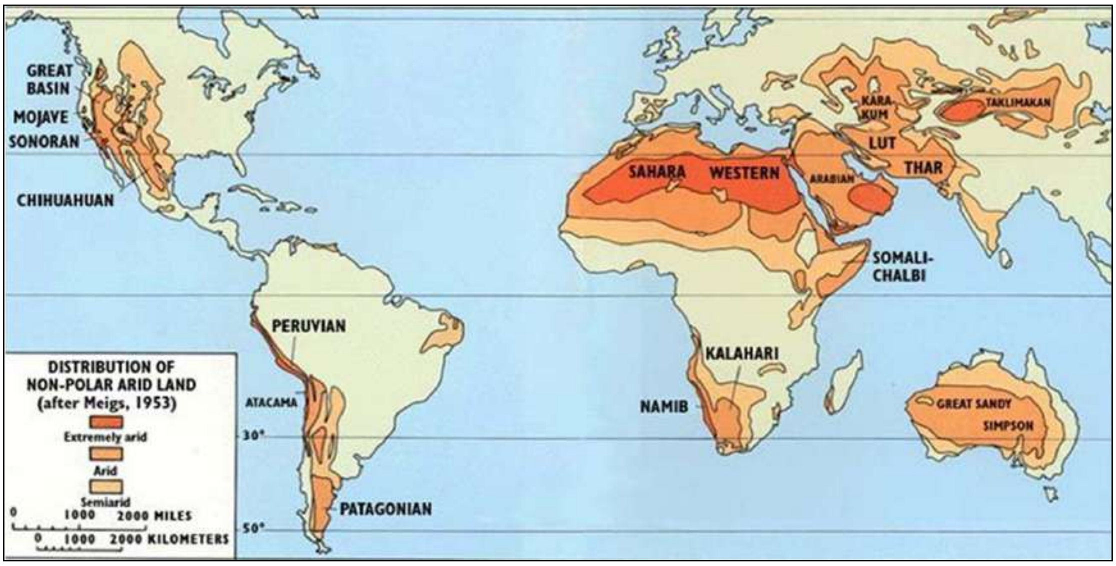
Aeolian Landform

Aeolian processes are those derived from wind activity, and they comprise erosion, transport, and sedimentation.

Small-sized particles are mobilized and, finally, deposited in different environments, sometimes at a great distance from their source area.

These are seen mostly in continental areas (deserts, dried rivers. lakes and its terraces, pediment covers and alluvial fans, lacustrine terraces). Marine beaches are also an important region to produce coastal dunes.

Aeolian Landform



Aeolian Landform: water influence

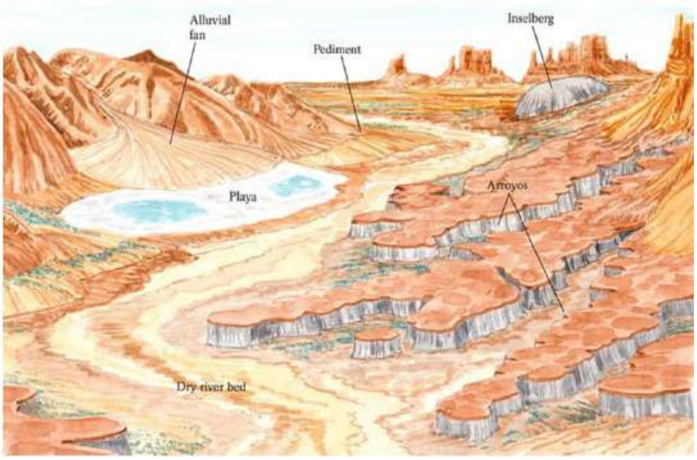
Bajada: broad slope of debris spread along the lower slopes of mountains by descending streams

Playa: Dried desert basins, occasionally filled with water

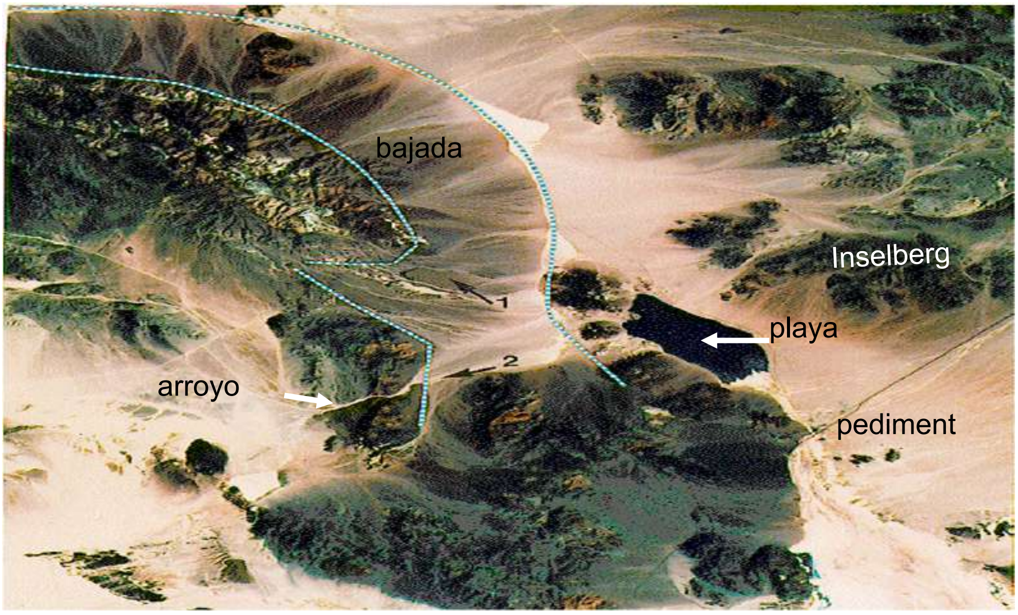
Pediment: Gently slopping surface at the base of steep slope

Arroyo: Dry river channel, often incised

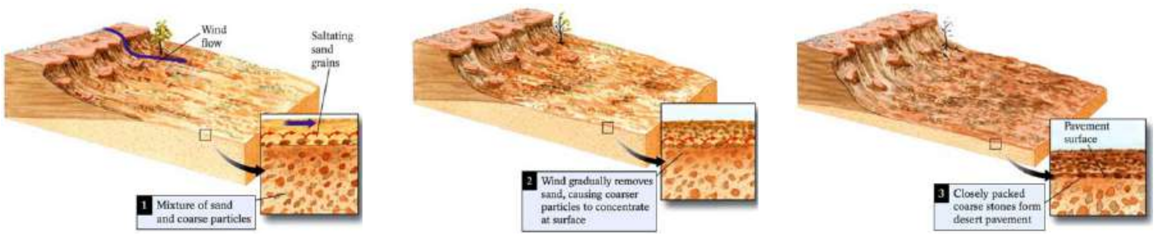
Inselberg: Isolated hill or ridge



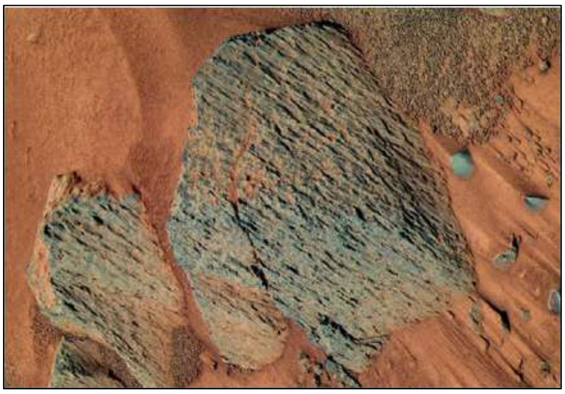
Aeolian Landform



Aeolian Landform: Pavements



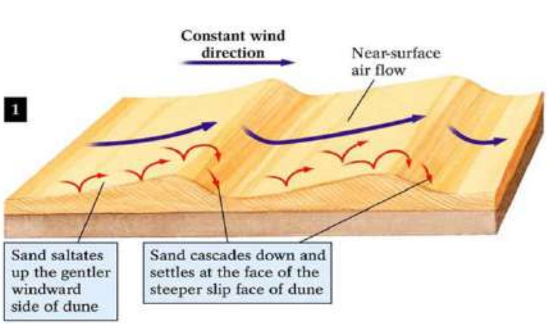
Aeolian Landform

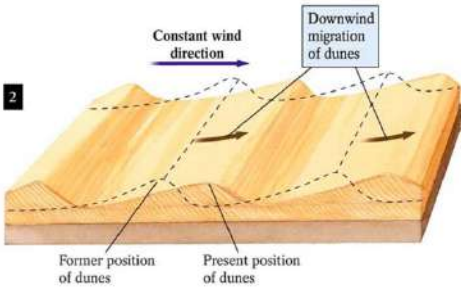


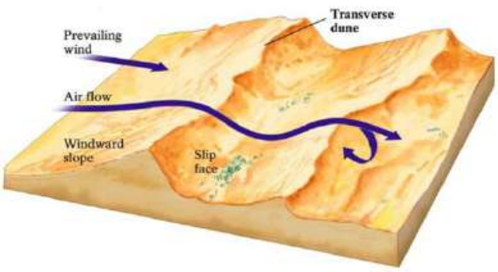
Ventifacts: Rocks that have been sculpted by wind-borne particles and worn, faceted, cut, or polished by the abrasive action of windblown sand.

Yardang: sharp irregular ridge of compact sand/rock lying in the direction of the current wind in exposed desert regions.

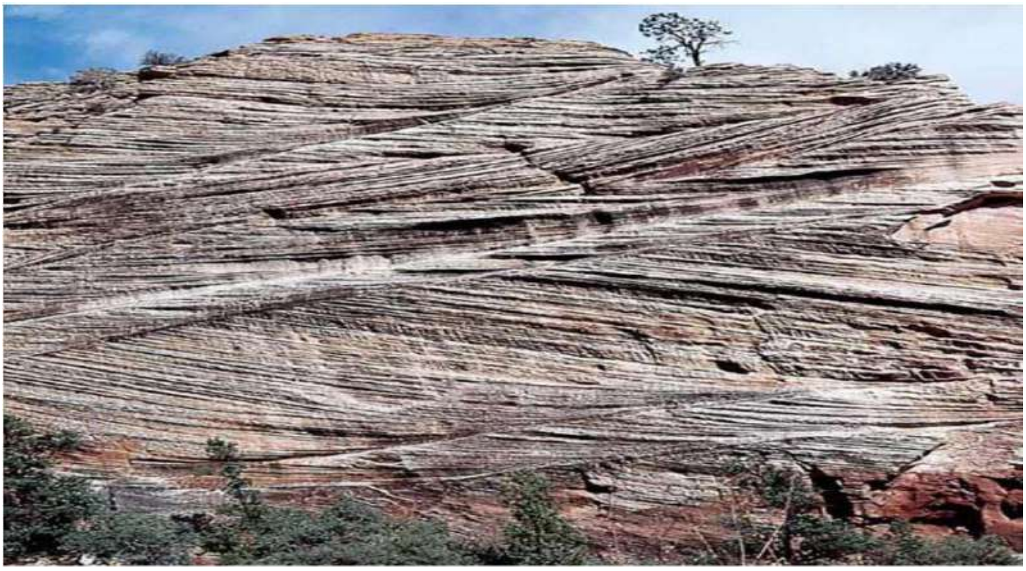
Aeolian Landform: Transverse Dunes



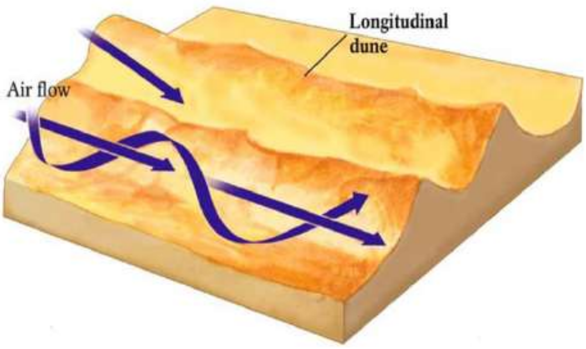




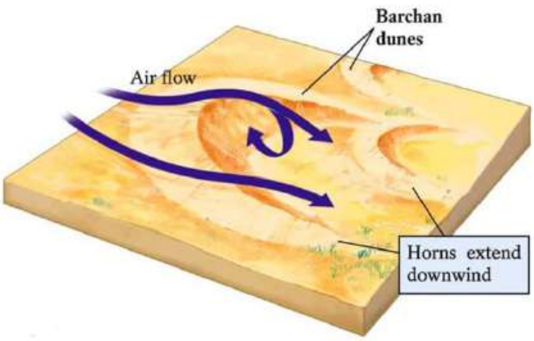
Aeolian Landform: Lithified Dunes



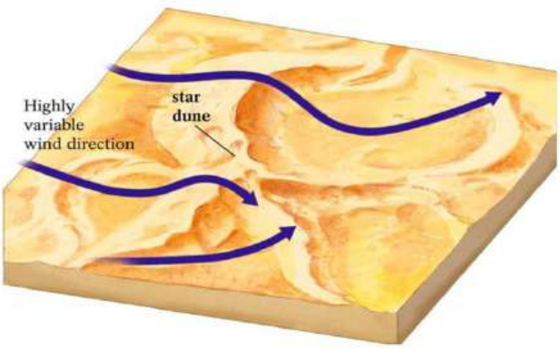
Aeolian Landform: Longitudinal Dunes



Aeolian Landform: Barchan Dunes



Aeolian Landform: Star Dunes



FLUVIAL LANDFORMS

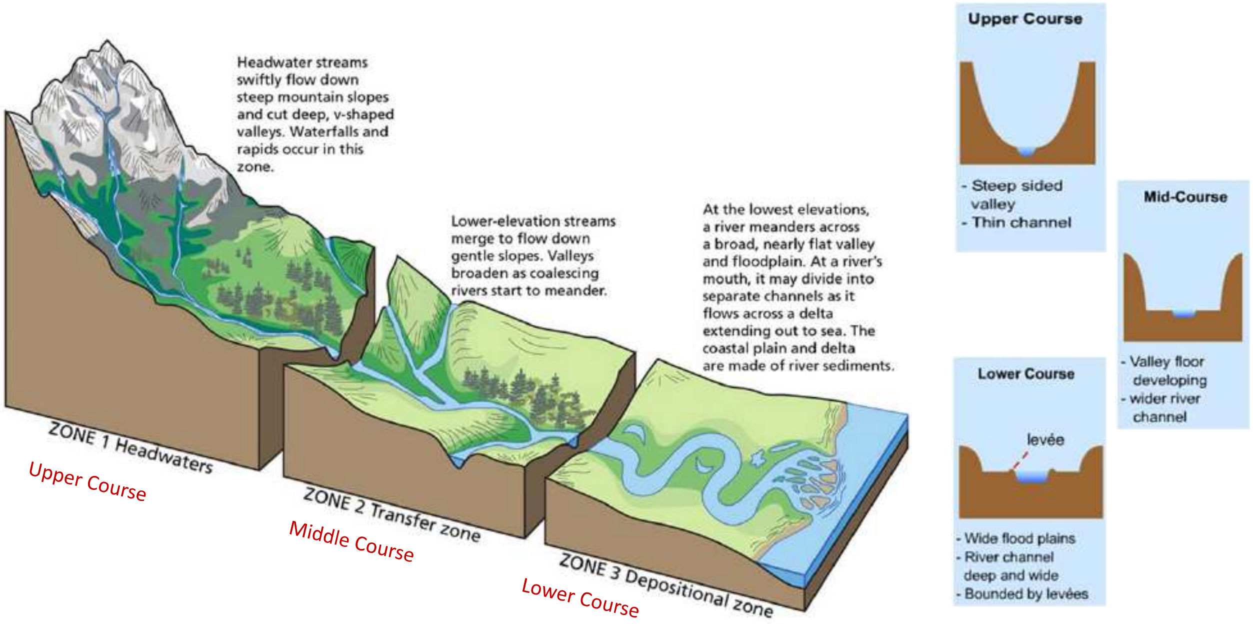
Fluvial Landform

- Open Channel Hydraulics and Downstream Changes:

  - Channel Hydraulics: Stream Discharge, Velocity, Stream Power, etc.
  - Stream Channel Flow and Stream Channel patterns
  - Longitudinal Profile of Stream Channel

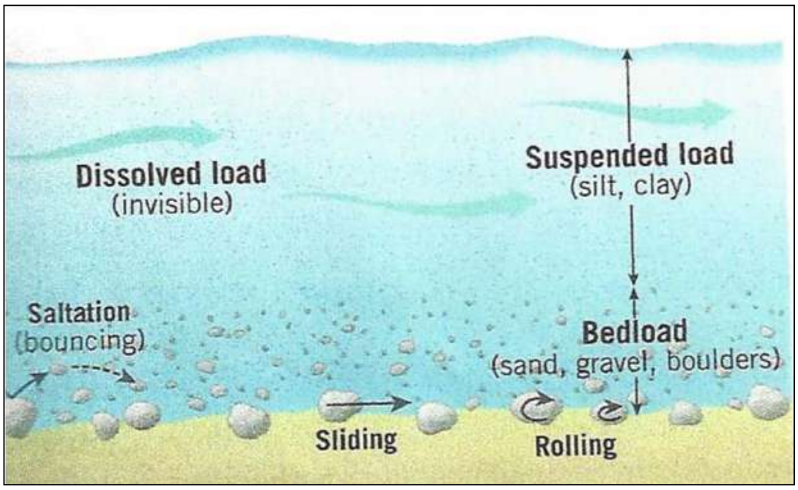
- Highways for moving people and goods
- Source of irrigation water for agriculture.
- Source of domestic and industrial water; hydro-electric Power
- Source of natural hazards
- River systems, as part of the hydrologic cycle

Fluvial Landform



Fluvial Landform

Sediments in a River



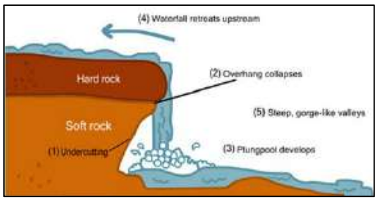
Headwaters (Upper Course):
Bedload

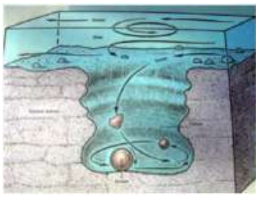
Transfer Zone (Middle Course):
Dissolved + Suspended + Bedload

Depositional Zone (Lower Course):
Dissolved + Suspended

Fluvial Landform: Headwaters

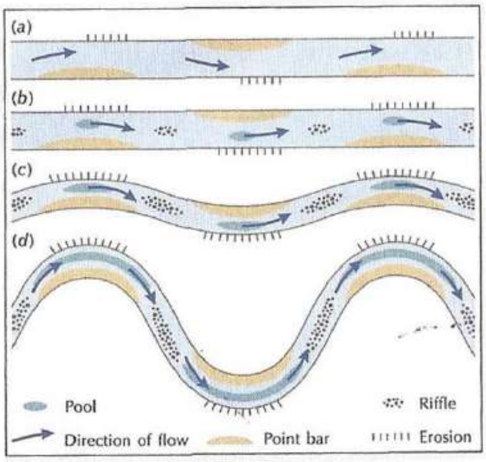
Waterfall; Canyon & Gorge; Underground Caves; Potholes; Rapids

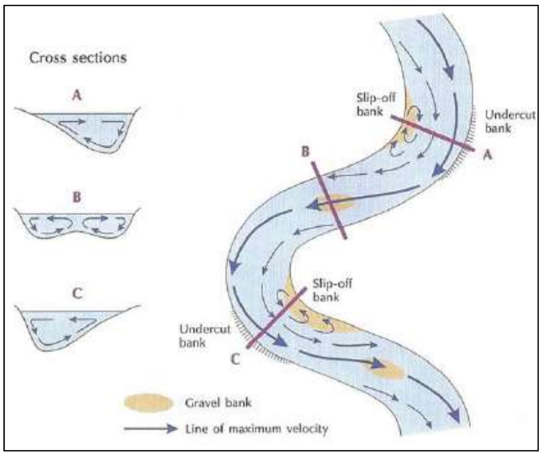




Fluvial Landform: Transfer Zone

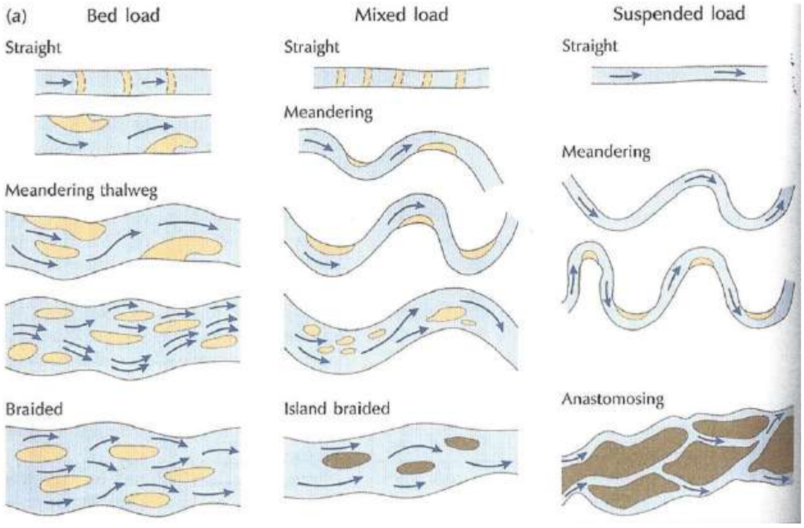
Sinuosity and meandering of a River





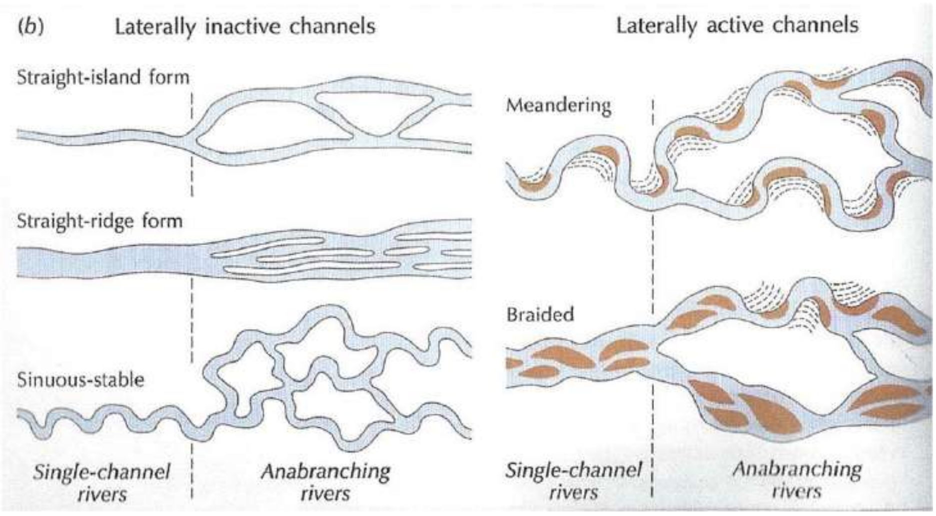
Fluvial Landform: Transfer/Depositional Zones

River Channel Patters

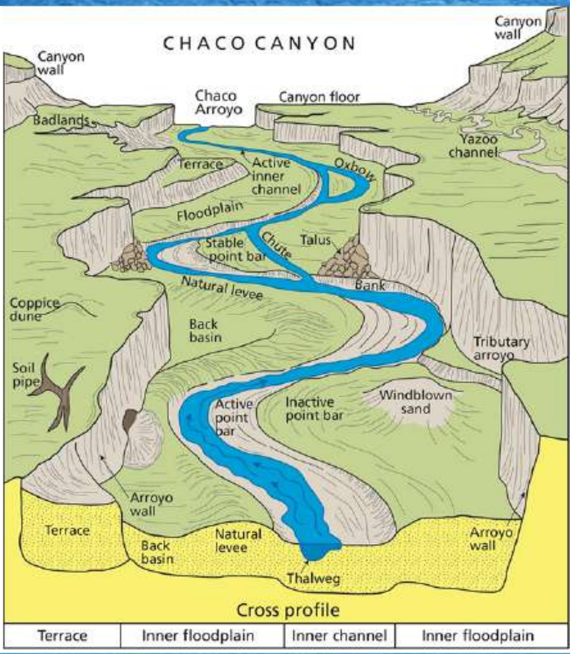


Fluvial Landform: Transfer/Depositional Zones

River Channel Patters



Fluvial Landform: Transfer/Depositional Zones



Fluvial Landform: Depositional Zone

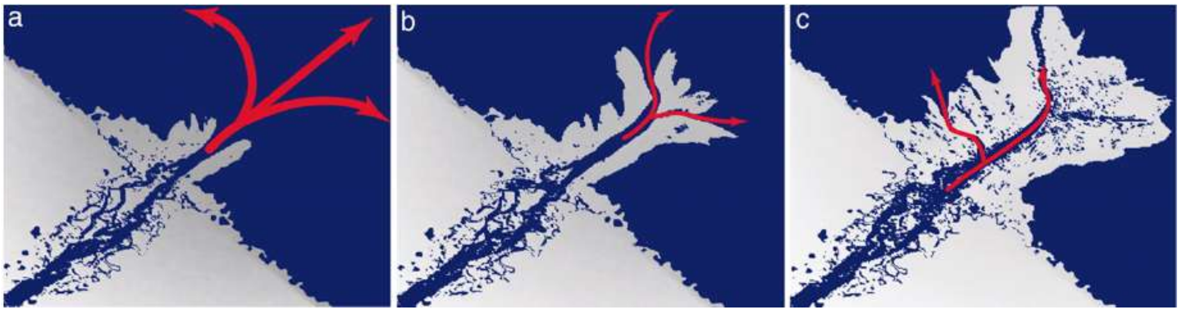
An ***estuary*** is an area where a freshwater river or stream meets the ocean – the mouth of the river. In *estuaries*, the salty ocean mixes with a freshwater *river*, resulting in brackish water. Brackish water is somewhat salty, but not as salty as the ocean. An *estuary* may also be called a bay, lagoon, sound, or slough

Fluvial Landform: Delta

Deltas are wetlands that form as *rivers* empty their water and sediment into another body of water (generally Ocean, sometimes lake or another river).

Fluvial Landform: Delta

Deltas are wetlands that form as *rivers* empty their water and sediment into another body of water (generally Ocean, sometimes lake or another river).



Seybold et al., 2007, PNAS

Next Lecture

Weathering & Erosion

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 38. Weathering & Erosion - I

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Experimental Rock Deformation Laboratory

Aims of this lecture

Concepts of Weathering and Erosion

Classification and Controlling factors of Weathering

Readings:
Grotinger & Jordan's Book: Chapter 16

Concept of Weathering and Erosion

In the last lecture we learnt: the Earth's topography is dynamic

However, natural forces always try to achieve an equilibrium

Weathering is the first step in flattening the high-lands (also an important part of Rock Cycle) and the Erosion (and mass wasting) takes the lead to move the weathered rock materials.

Concept of Weathering and Erosion

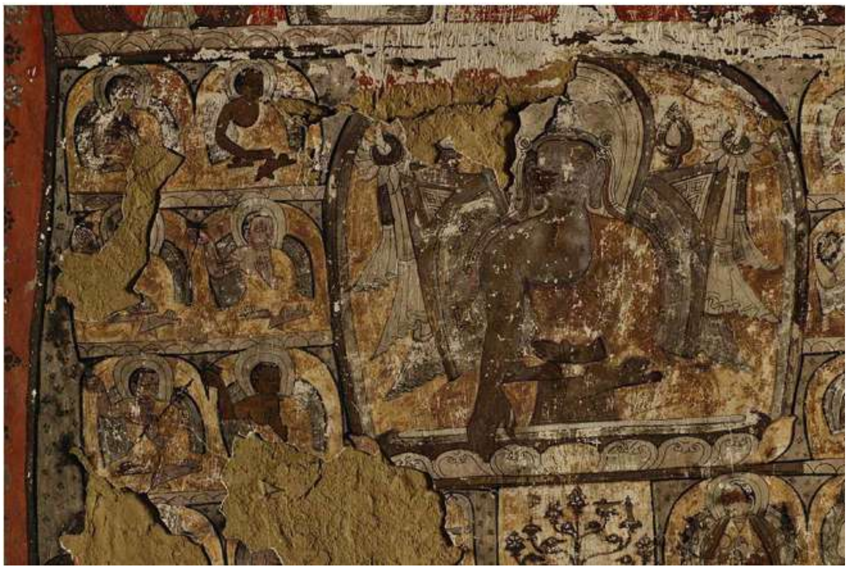
Weathering is the breaking down or dissolving of rocks and minerals on Earths surface

Erosion generally refers to processes that move Earth materials on a grain-by-grain basis.

Mass wasting refers to processes that cause large masses of material to collapse and move downslope.

Weathering?

Weathering?



Ritseling Cave in Upper Mustang, Nepal. (NatGeo)

Controlling factors of Weathering

	WEATHERING RATE		
	SLOW	Medium	FAST
PROPERTIES OF PARENT ROCKS			
Mineral solubility in Water	Low (quartz)	Moderate (pyroxene, feldspar)	High (calcite)
Rock Structure	Massive	Some zones of weakness	Highly fractured/layered
CLIMATE			
Rainfall	Low	Moderate	High
Temperature	Cold	Temperate	Hot
PRESENCE OR ABSENCE OF SOIL AND VEGETATION			
Thickness of soil layer	None-bare rock	Thin to moderate	Thick
Organic content	Low	Moderate	High
LENGTH OF EXPOSURE			
	Short	Moderate	Long

Classification of Weathering

Physical (mechanical) weathering: Rock material does NOT change, i.e., composition remains same

Examples: Hitting, frost action, scratching (abrasion), breaking from changes in temp., pressure or living organisms

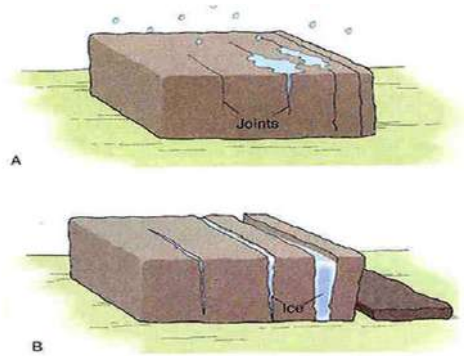
Chemical weathering: Rock material is changed into another substance.

Examples: Oxidation (exposure to air), Acid (acid rain), Hydrolysis (Water)

Physical Weathering

Frost Wedging

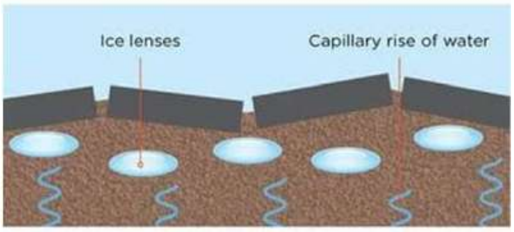
Water seeps into cracks in rocks ;then freezes and expands causing the rock to crack.



Physical Weathering

Frost Heaving

The upward or outward movement of the ground surface (or objects on, or in, ground) caused by formation of ice in soil.



Physical Weathering

Salt Wedging

Saltwater seeps into rocks and then evaporates on a hot sunny day. Salt crystals grow within cracks and pores in the rock, and the growth of these crystals can push grains apart, causing the rock to weaken and break. Common in rocky shorelines.

Tafoni (Honeycomb weathering) in sandstone on Gabriola Island, British Columbia. The holes are caused by crystallization of salt within rock pores.

Physical Weathering

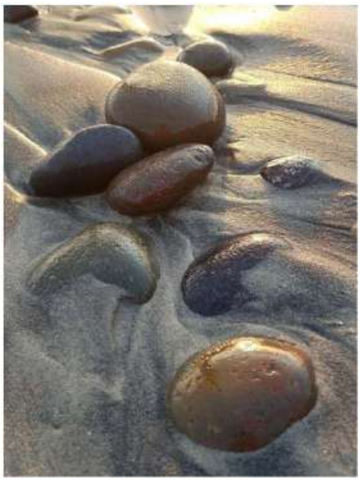
Plant roots

Plants roots grow into rocks and cohesive aggregates and crack them.

Physical Weathering

Friction and Repeated Impacts

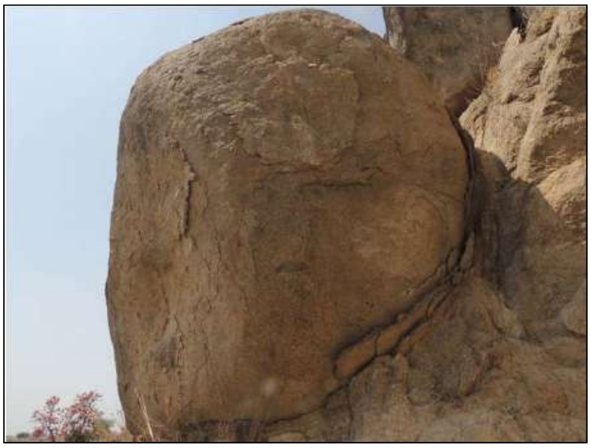
Actions of flowing water, wind and glacier break and smoothen the rocks



Physical Weathering

Thermal expansion and Contraction

The outer layer of the rock is heated by the sun which causes it to **expand**, and, as it cools during the night, it **contracts**. This expanding and contacting causes the outer layer of the rock to peel away. The process also breaks the rocks along pre-existing joints and cracks.



Physical Weathering

Organic Activities

Burrows by animals, insects and worms

Chemical Weathering

Resistance to Chemical Weathering

Stability of Minerals	Rate of Weathering
MOST STABLE	Slowest
Iron oxides (hematite)	↓
Aluminum hydroxides (gibbsite)	
Quartz	
Clay minerals	
Muscovite mica	
Orthoclase feldspar	
Biotite mica	
Sodium-rich plagioclase feldspar (albite)	
Amphiboles	
Pyroxenes	
Calcium-rich plagioclase feldspar (anorthite)	
Olivine	
Calcite	
Halite	
LEAST STABLE	Fastest

Unweathered granite is hard and solid because an interlocking network of feldspar, quartz, and other crystals holds it tightly together.
When the feldspar is transformed by weathering into a loosely adhering clay, the network is weakened and the mineral grains are separated.

Chemical weathering, by producing the clay, also promotes physical weathering because the rock now fragments easily along widening cracks at the boundaries between grains.

Chemical Weathering

Dissolution

Dissolution weathering produce ions, but no minerals, and are reversible if the solvent is removed (think of dissolving salt in a glass of water). Natural Halite, Gypsum and anhydrite are other minerals that will dissolve in water alone. Calcite, will dissolve in acidic water (*Carbonation*).

Sinkhole downstream of the Mosul Dam in Iraq. The sinkhole is a result of dissolution of gypsum and anhydrite layers.

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow HCO_3^- + H^+$$

$$CaCO_3 + H_2CO_3 \rightarrow 2HCO_3^- + Ca^+$$

Chemical Weathering

Hydrolysis

Hydrolysis as a chemical reaction where water loosens the chemical bonds within a mineral. This is different from Dissolution, as it produces new minerals, with or without ions.

$$\underset{\text{K-Feldspar}}{2KAlSi_3O_8} + \underset{\text{Water}}{3H_2O} \rightarrow \underset{\text{Kaolinite}}{Al_2Si_2O_5(OH)_4} + \underset{\text{Quartz}}{4SiO_2} + \underset{\text{Ions}}{2K+ + 2OH-}$$

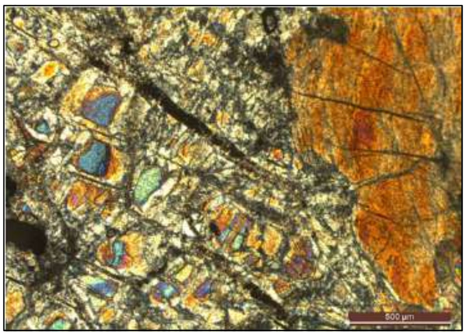
Chemical Weathering

Hydrolysis

Hydrolysis as a chemical reaction where water loosens the chemical bonds within a mineral. This is different from Dissolution, as it produces new minerals, with or without ions.

$$\underset{\text{Olivine}}{(MG,Fe)_2SiO_4} + \underset{\text{Water}}{3H_2O} \rightarrow \underset{\text{Serpentine}}{(MG,Fe)_3SiO_5(OH)_4} + \underset{\text{Brucite}}{(MG,Fe)(OH)_2} + \underset{\text{Magnesite}}{Fe_3O_4} + H_2$$

Serpentine (hand specimen)



Serpentine (thin section)

Chemical Weathering

Hydrations

Hydration reactions involve water being added to the chemical structure of a mineral.

$$\underset{\text{Anhydrite}}{CaSO_4} + \underset{\text{Water}}{3H_2O} \rightarrow \underset{\text{Gypsum}}{(CaSO_4).2H_2O}$$

$$\underset{\text{Hematite}}{2Fe_2O_3} + 3HOH \rightarrow \underset{\text{Limonite}}{2Fe_2O_3\ .3H_2O}$$

$$\underset{\text{Bauxite}}{Al_2O_3} + 3HOH \rightarrow \underset{\text{Hyd. Aluminum Oxide}}{Al_2O_3\ .3H_2O}$$

Chemical Weathering

Oxidation

Oxidation happens when free oxygen is involved in chemical reactions. *[Oxidation reactions provide valuable insight into Earth's early surface conditions: transition in the rock record from rocks containing no minerals that are products of oxidation reactions, to rocks containing abundant minerals produced by oxidation. This reflects a transition from an oxygen-free atmosphere to an oxygenated one]*

$4FeO$ (Ferrous oxide) + O_2 → $2Fe_2O_3$ (Ferric oxide)
$4Fe_3O_4$ (Magnetite) + O_2 → $6Fe_2O_3$ (Hematite)
$2Fe_2O_3$ (Hematite) + $3H_2O$ → $2Fe_2O_3 .3H_2O$ (Limonite)

Chemical Weathering

Oxidation

The oxidation reaction begins in Olivine with taking iron out of the mineral and putting it into solution as an ion. Olivine reacts with carbonic acid, leaving dissolved iron, bicarbonate, and silicic acid:

$$Fe_2SiO_4 + 4H_2CO_3 \rightarrow 2Fe_2^{+} + 4HCO_3^{-} + H_4SiO_4$$

Iron and oxygen dissolved in water react in the presence of bicarbonate to produce hematite and carbonic acid:

$$2Fe_2^{+} + ½ O_2 + 2H_2O + 4HCO_3^{-} \rightarrow Fe_2O_3 + 4H_2CO_3$$

Chemical Weathering

Oxidation

Oxidation applies to almost any other ferromagnesian silicate, including pyroxene, amphibole, or biotite.

Iron in the sulphide minerals (e.g., pyrite) can also be oxidized in this way.

Chemical Weathering

Acid Rock Drainage (ARD)

If rocks have elevated levels of sulphide minerals, oxygen and water react with them and the runoff areas are known as Acid Rock Drainage. Also possible in mines (Acid Mine Drainage – AMD). metals such as copper, zinc, and lead easily dissolve in water, which can be toxic to aquatic life and other organisms.

Weathering: Controls and Rates

Now, if you go back to slide 7; you will understand better the controlling factors and rates of weathering.

Clearly, weathering does not happen at the same rate in all environments. The same types of weathering do not happen in all environments.

CLIMATE

O_2 **CO_2**

Minerals

Next Lecture

Weathering & Erosion - II

Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 39. Weathering & Erosion - II

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Experimental Rock Deformation Laboratory

Aims of this lecture

Soil formation and characteristics

Erosion and mass Movement

Readings:
Grotinger & Jordan's Book: Chapter 16

SOIL

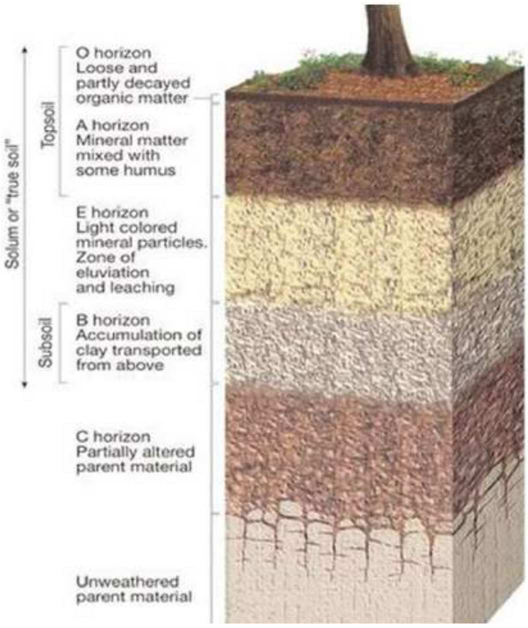
What is Soil?

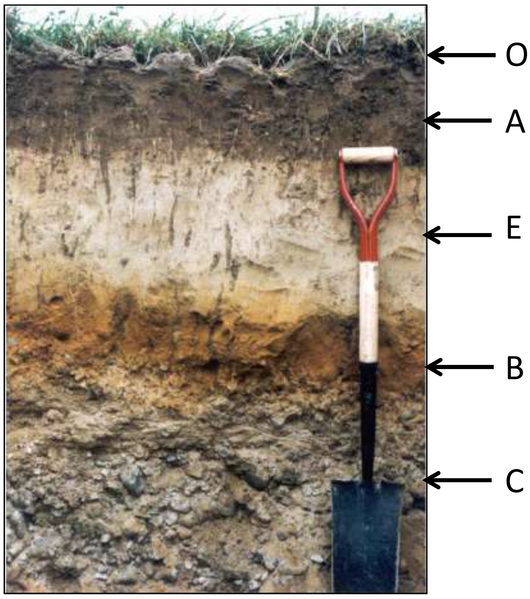
Weathering is a key part of the process of soil formation.

Soil is a complex mixture of minerals (~45%), organic matter (~5%), and empty space (~50%, filled to varying degrees with air and water). The mineral content of soil varies, but is dominated by clay minerals and quartz, along with minor amounts of feldspar and small fragments of rock.

The types of weathering that take place within a region have a major influence on soil composition and texture.

Soil Profile





Soil Profile

The A horizon is further sub-divided into four horizons:

- (L) leaf litter
- (F) fermenting leaf litter
- (H) humus
- (E) eluvial

These lie above the B horizon.

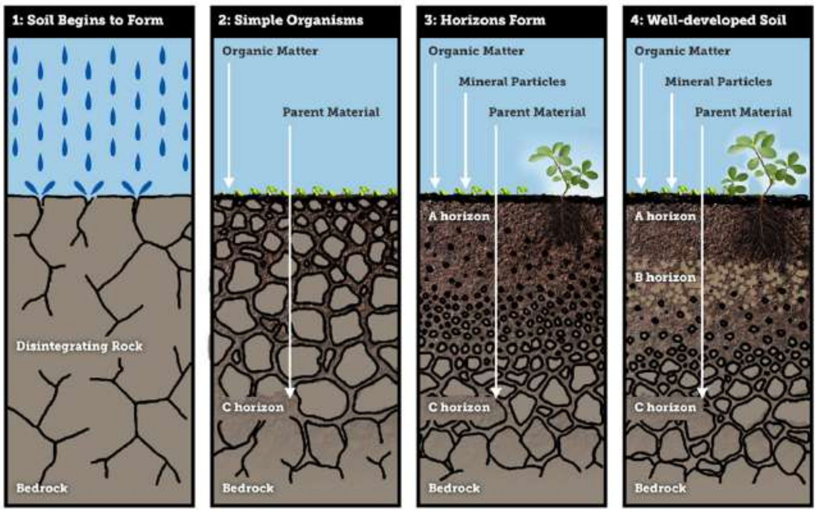
Formation of Soil

Soils develop as a result of the interplay of 5 factors; Parent material, climate, organisms, relief and time.

SOIL FORMING FACTORS

- Parent material
- Climate
- Organisms: vegetation, fauna and soil biota
- Relief (landforms and topography)
- Time

Formation of Soil



TOPSOIL, upper or A horizon

SUBSOIL, middle or B horizon

PARENT MATERIAL, lower or C horizon

Parent Materials

This is the material from which the soil develops and can vary from solid rock to deposits like alluvium and boulder clay.

The parent material can influence the soil in a number of ways:

- colour
- texture
- structure
- mineral composition
- permeability/drainage

This soil has developed on Old Red Sandstone and so has derived its distinctive colour from its parent material.

Climate

Contrasting soils can be produced from the same parent material under different climates.

Climate has two major components: moisture (precipitation) and temperature,

Soil forms most readily under temperate to tropical conditions, and moderate precipitation.

When precipitation exceeds evaporation, leaching of the soil will occur.

Temperature determines the rate of reactions; chemical and biological decay and so has an influence on weathering and humification.

Organic Matter

Organisms influencing soil development range form microscopic bacteria to large animals including human. Micro organisms such as bacteria and fungi assist in the decomposition of plant litter. This litter is mixed into the soil by macro organisms (soil animals) such as worms and beetles.

Soil horizons are less distinct when there is much soil organism activity.

Higher plants influence the soil in many ways. The nature of the soil humus is determined by the vegetation cover and resultant litter inputs. Roots contribute dead roots to the soil, bind soil particles together and can redistribute and compress soil.

Organic Matter

Rate of degradation, $\frac{dC}{dt} = A - rC$

A – annual addition of organic matter
C – amount of organic matter already in soil
r – decomposition constant

r – direct measure of CO_2 production in soil; important to determine the rate of chemical weathering

If soil is in equilibrium, $\frac{dC}{dt} = 0$; and $A = rC_e$

where C_e is the equilibrium concentration of carbon

Organic Matter

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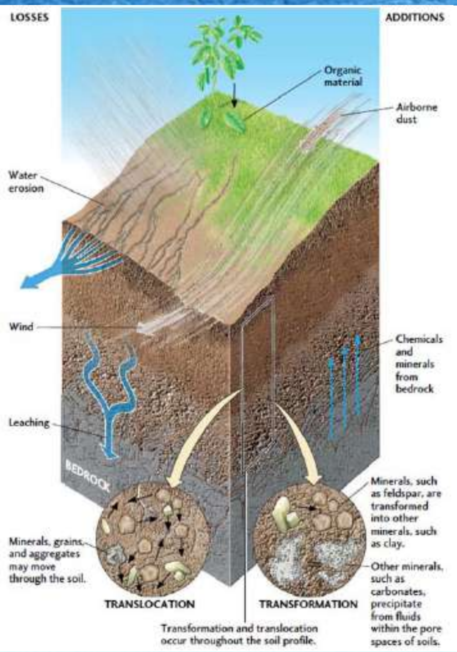
Formation of Soil



As soil ages and matures, the materials added to or removed from it cause it to undergo a set of *transformations*. (Addition of humus; chemical and mechanical weathering etc.)

Translocations are lateral and vertical movements of materials within the developing soil. Water is the main agent of translocation, usually transporting dissolved salts and other minerals and nutrients (Leaching).

See Table 16-3 of the text book for different soil types (page 448)

Erosion & Mass Movement

Erosion

Erosion is defined as removal of rocks and soil by wind, water, ice and gravity.

Wind*, water*, ice* and gravity are also known as the agents of erosion.

Remember: Weathering breaks-down rocks and Erosion transports the fragments (sediments)

*we already learnt

Gravity induced Erosion: Mass Movement

Gravity Erosion is better known as Mass Movement and is defined as the transfer of rock and soil down slope by direct action of gravity without a flowing medium (such as water or ice).

Some of the best examples of Mass Movement are:

Creep; Rock fall; Slump; Landslides; Avalanches

When the right combination of materials, moisture, and steepness makes a slope unstable, a mass movement is inevitable. All that is needed is a trigger.

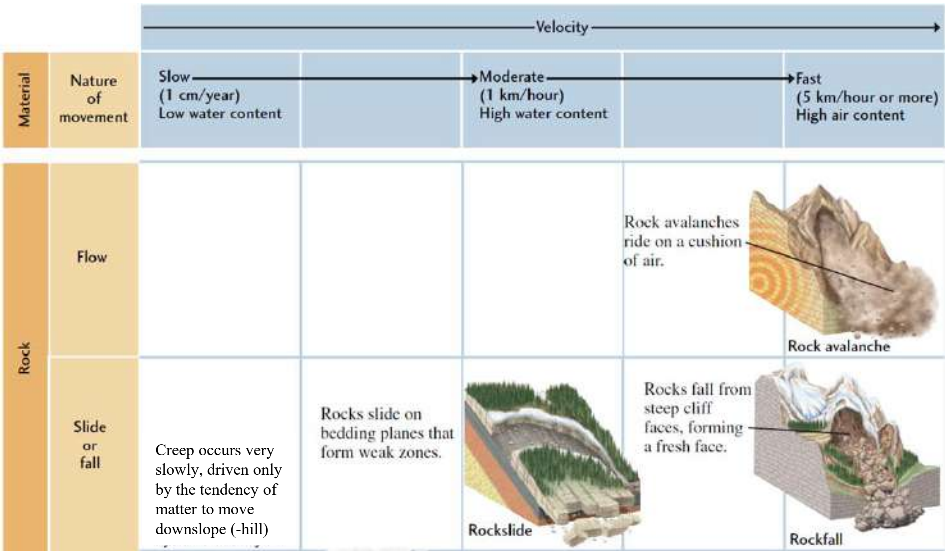
Mass Movement: Classification

The nature of the moving material (for example, whether it is rock or unconsolidated material)

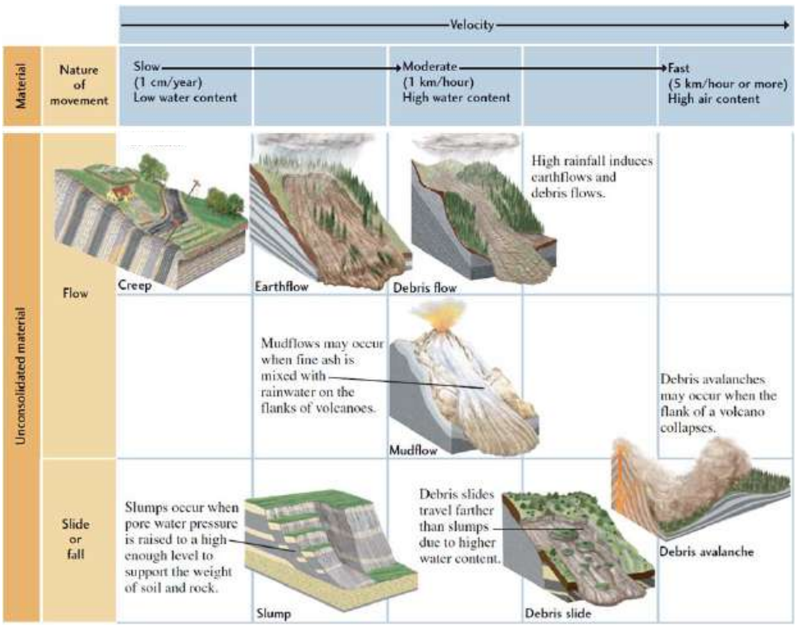
The velocity of the movement (from a few centimeters per year to many kilometers per hour)

The nature of the movement: whether it is sliding (the bulk of the material moves more or less as a unit) or flowing (the material moves as if it were a fluid)

Mass Movement: Classification



Mass Movement: Classification



Mass Movement: Classification

Mass Movement: Classification

Mass Movement: Classification



Mass Movement: Classification


Next Lecture

Resources of the Earth

GROUNDWATER

1

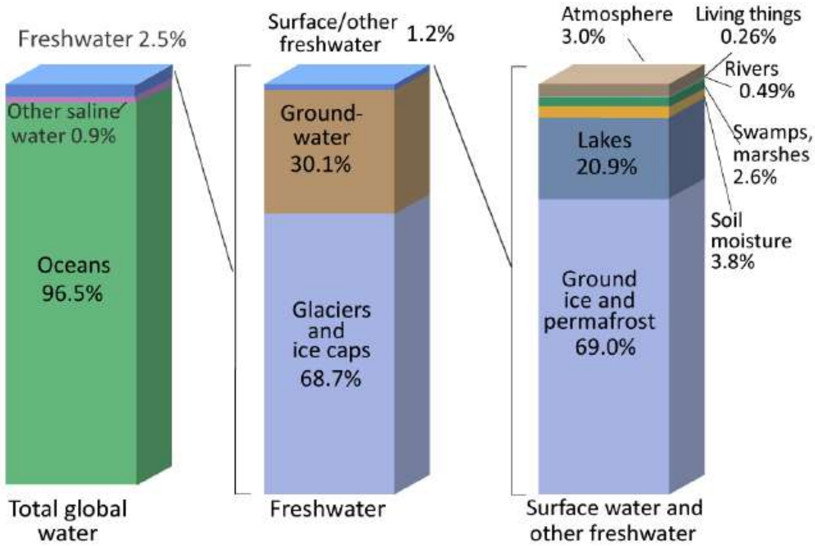
Basics of Groundwater

- Groundwater is one of the most widely available natural resources.
- Groundwater also represents the largest reservoir of freshwater readily available to man.
- The value of ground water, in terms of both economics and human welfare, is incalculable.
- Consequently, its sound development, diligent conservation, and consistent protection from pollution are important concerns of everyone.

2

2

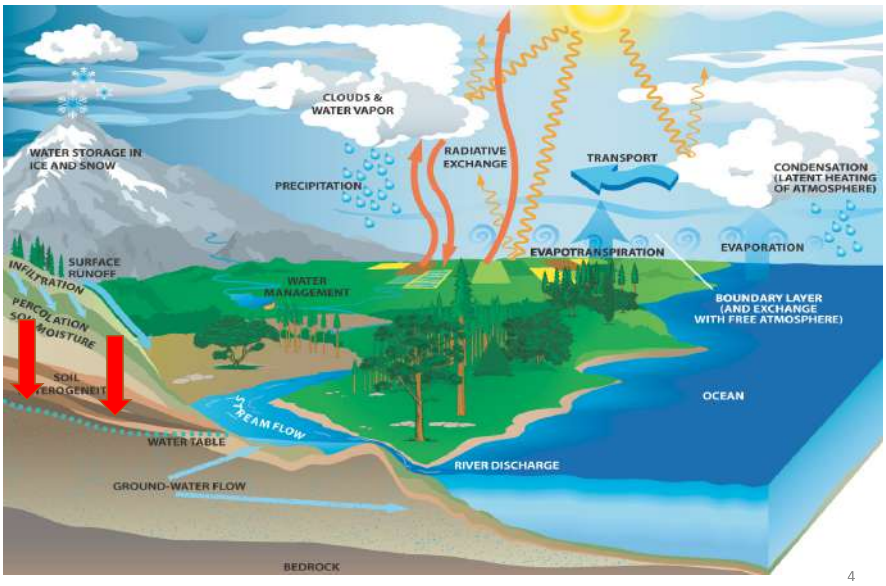
Distribution of Earth's water



Source: Igor Shiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources. (Numbers are rounded).

3

Origin of Groundwater: Hydrologic Cycle



4

Hydrologic Cycle

- Essentially composed of natural storages and fluxes (e.g. ocean (storage) & precipitation (flux))
- A dynamic system constantly powered by the solar radiation and embraced by constant flow.
- A recycling system which enables water to remain clean.
- Almost all groundwater can be thought as a part of the hydrologic cycle including surface and atmospheric water.

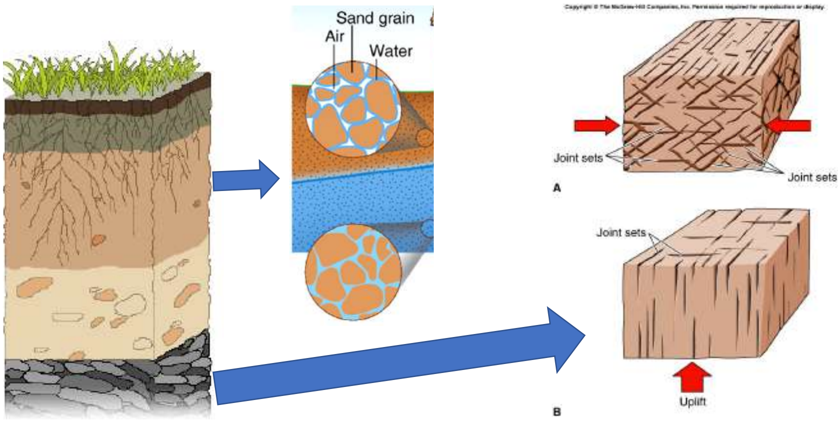
Thus, practically all groundwater originates as surface water

5

5

Where does water occur underneath the ground?

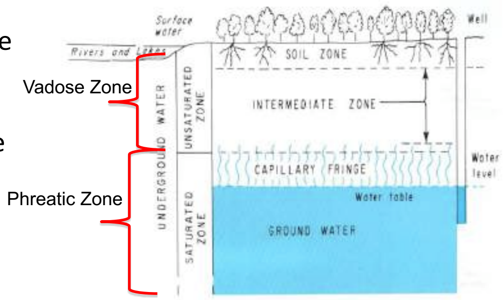
- Water fills up the spaces between soil particles and within the cracks and fractures in rocks.



6

Are all type of subsurface water termed as groundwater ?

- Water present in the sub surface openings that are completely saturated: **Groundwater**
- Water existing in the subsurface openings that comprise of both water and air: **Soil Moisture**
- **Groundwater** occurs in the Phreatic Zone while **Soil Moisture** occurs in the Vadose Zone



7

Occurrence of groundwater

- **Subsurface water** occurs in the void spaces of earth materials that range from consolidated rocks (Igneous, Metamorphic and Sedimentary rocks) to unconsolidated materials (ranging in size from fractions of a millimeter (clay size) to several meters (boulders)).
- **Groundwater** is that part of subsurface water in which the interstices are completely saturated with water
- Groundwater can be found in all three classes of rocks, but in general, the sedimentary rocks contain by far the greatest amounts of water due to their greater *porosity.*

Surface Reservoirs	Subsurface Reservoirs
Disadvantages	Advantages
High evaporative loss, even where humid climate prevails	Practically no evaporative loss
Need large areas of land	Need very small areas of land
May fail catastrophically	Practically no danger of failure
Varying water temperature	Water temperature uniform
Easily polluted	Usually high biological purity, although pollution can occur
Easily contaminated by radioactive fallout	Not rapidly contaminated by radioactive fallout
Water must be conveyed	Act as conveyance systems, thus obviating the need for pipes or canals

8

8

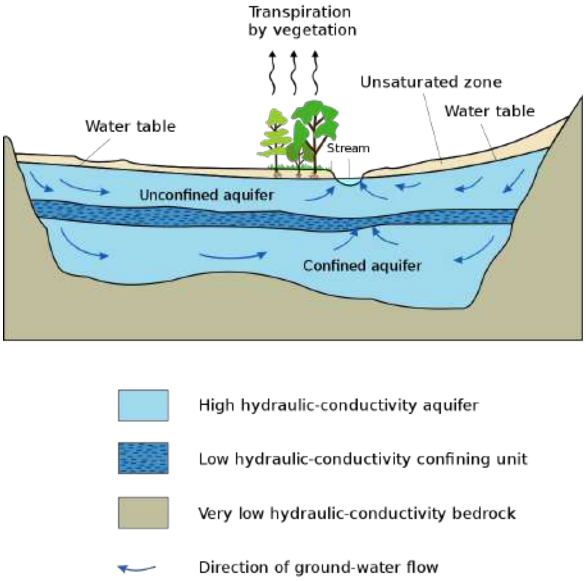
Types of natural storage

- An **aquifer** is a geologic unit that can store and transmit water at sufficient rates to supply wells.
- A **confining layer** is a geologic unit that has low to no intrinsic permeability (which is a measure of the how water flows through the rock layer).
- An aquifer is always underlain by a confining layer.
- Confining layers are subdivided into **aquifuges** (absolutely impermeable) and **aquitards** (impermeable relative to the adjacent units)
- Water table aquifers, those with no confining layer above, are called **unconfined aquifers**.
- Aquifers overlain by a confining layer are called **confined aquifers**

9

9

Types of natural storage



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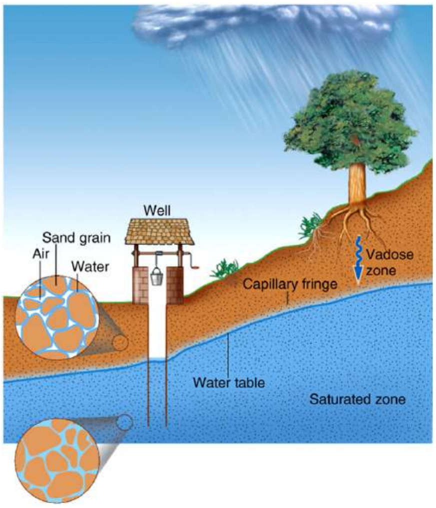
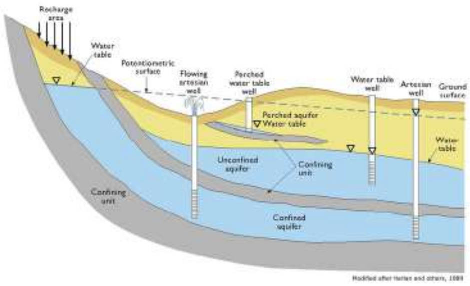


- **Water table** is the surface separating the vadose zone from the saturated zone.
- The water table is the level at which water in a well will stand.
- **Recharge** is termed as the process by which groundwater storage is replenished.



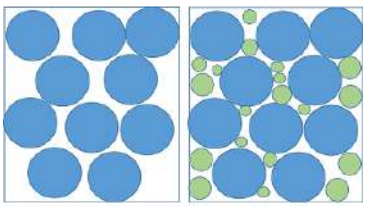
11

Important Hydraulic Properties of Earth Materials and Groundwater

- **Porosity** (n) determines how much water a rock or soil can hold and is defined as the volume of the pores of a rock or soil sample (V_v) divided by the total volume (V_T) of both pores and solid material, that is

$$n = \frac{V_v}{V_T}$$

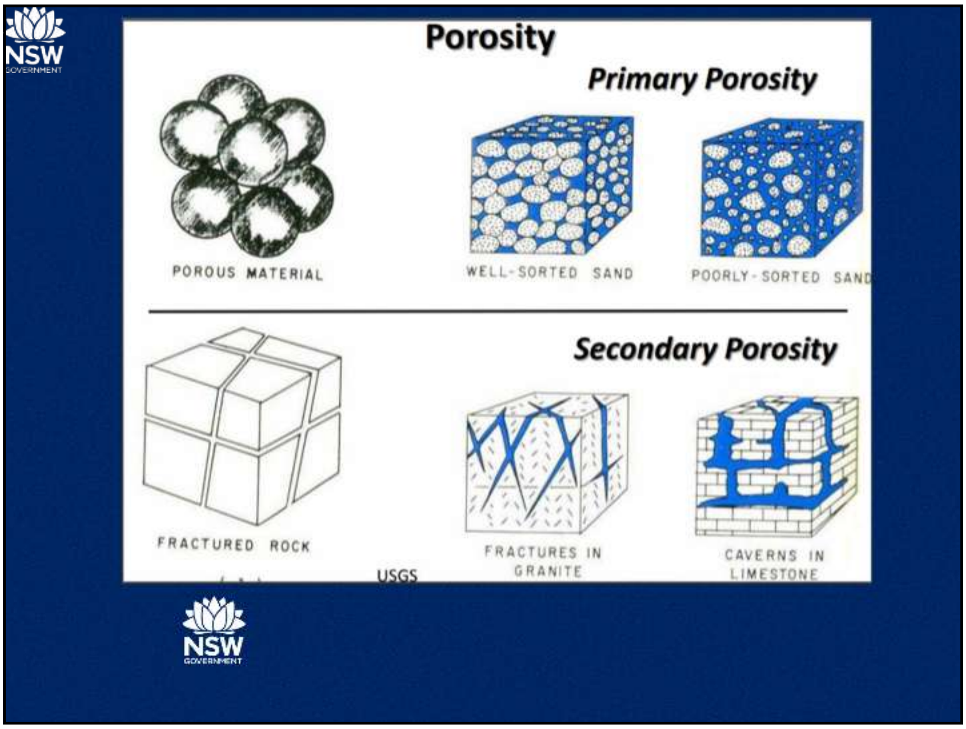
- Porosity has the units of $\frac{L^3_{voids}}{L^3_{R.E.V.}}$.
- It is a measure of the storage capacity



High porosity – large spaces   Low porosity – small spaces

12

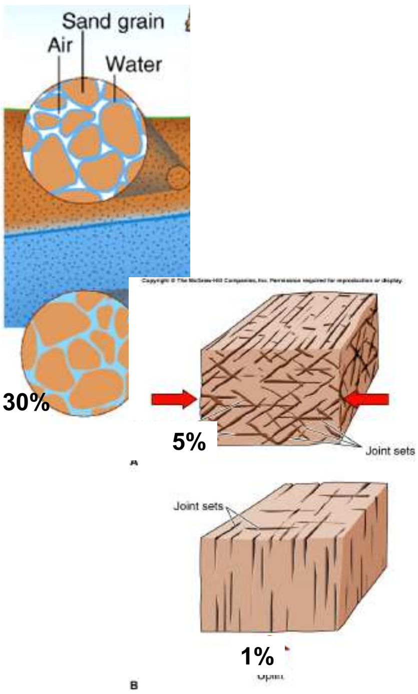
12



13

Porosity

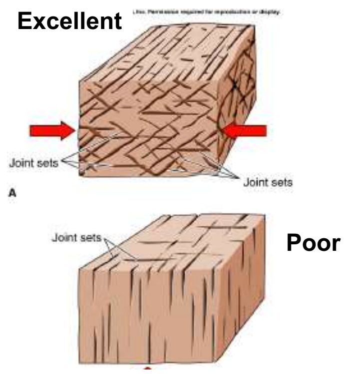
- **Unconsolidated sediments**: Determined by how tightly packed and how clean (silt and clay), (usually between 20 and 40%)
- **Rock**: Determined by size and number of fractures (most often very low, <5%)
- Extent of weathering



14

Permeability

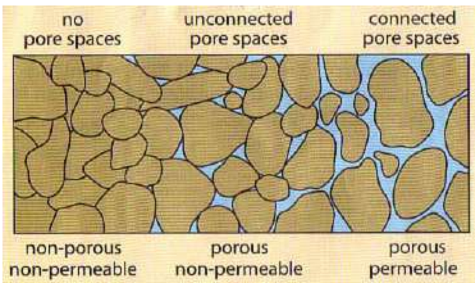
- Measure of the ease with which water will flow through a porous material
  - **Sediment**: Proportional to sediment size
    - Gravel→Excellent
    - Sand→Good
    - Silt→Moderate
    - Clay→Poor
  - **Rock**: Proportional to fracture size and number.
  - Continuity of the fractures
  - Can be good to excellent



15

Porosity and Permeability

- Permeability is **not proportional** to porosity.
- A rock may be extremely porous, but if the pores are not connected, it will have no permeability.
- Likewise, a rock may have a few continuous cracks which allow ease of fluid flow, but when porosity is calculated, the rock doesn't seem very porous.



Sediment	Porosity (%)	Permeability
Gravel	25 to 40	excellent
Sand (clean)	30 to 50	good to excellent
Silt	35 to 50	moderate
Clay	35 to 80	poor
Glacial till	10 to 20	poor to moderate

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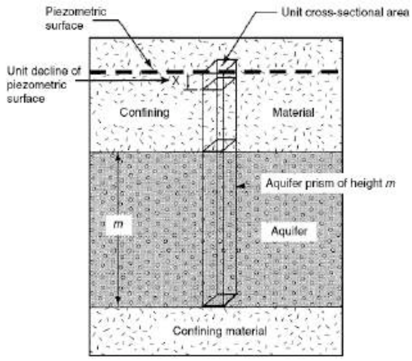
Storage Coefficient (Storativity (S)/Specific Yield(S_y))

- Storativity/Specific Yield is defined as the volume of water per unit aquifer surface area taken into or released from storage per unit increase or decrease in head respectively.
- Hence Storativity (S) and Specific Yield (S_y)are both measures of water yield from aquifers. The difference is that S is specifically used for confined aquifers, whereas S_y is to unconfined aquifers only.
- It is a dimensionless quantity. In confined aquifers the value of storativity ranges from 0.005 to 0.00005.
- Typical range of S_y is 0.02 to 0.3



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Groundwater Yield

- For an unconfined aquifer the value of S_y is typically several orders of magnitude greater than the value of *S*.
- The volume of water drained from an aquifer due to the drop in hydraulic head can be estimated from the formula

$$V_w = S.A.\Delta h$$

- where V_w is the volume of water released, *S* is the storativity (S_y incase of unconfined aquifers), *A* is the surface area of the drained aquifer, and Δh is the decline in hydraulic head/water table.

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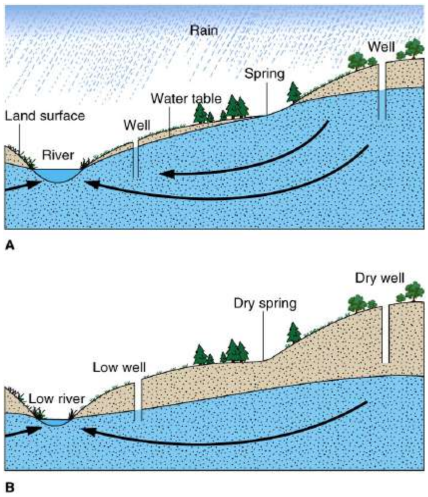
Darcy's Law
Answers the fundamental questions of hydrogeology.

- What controls:
  - How much groundwater flows?
  - How fast groundwater flows?
  - Where groundwater flows?

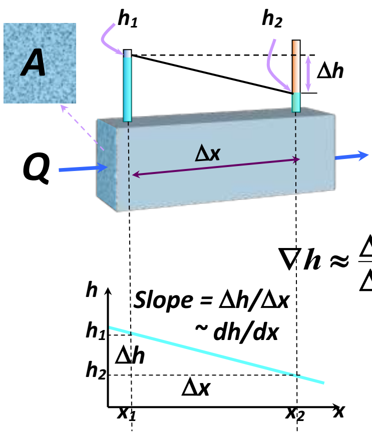


19

Darcy's Law

Henry Darcy's Experiment (Dijon, France 1856)

Darcy investigated ground water flow under controlled conditions



$$Q \propto \Delta h, \quad Q \propto 1/\Delta x, \quad Q \propto A$$

Q: Volumetric flow rate [L^3/T]

A: Cross Sectional Area

K: The proportionality constant is added to form the following equation:

$\nabla h \approx \dfrac{\Delta h}{\Delta x}$: Hydraulic Gradient

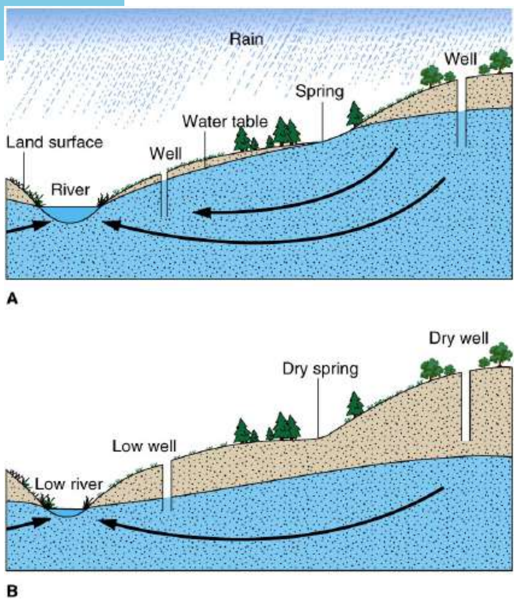
$$Q \propto A\frac{\Delta h}{\Delta x} \quad \Rightarrow \quad Q = -K A\frac{\Delta h}{\Delta x}$$

K units [L/T]

20

Natural Water Table Fluctuations

- Infiltration
  - Recharges ground water
  - Raises water table
  - Provides water to springs, streams and wells
- Reduction of infiltration causes water table to drop



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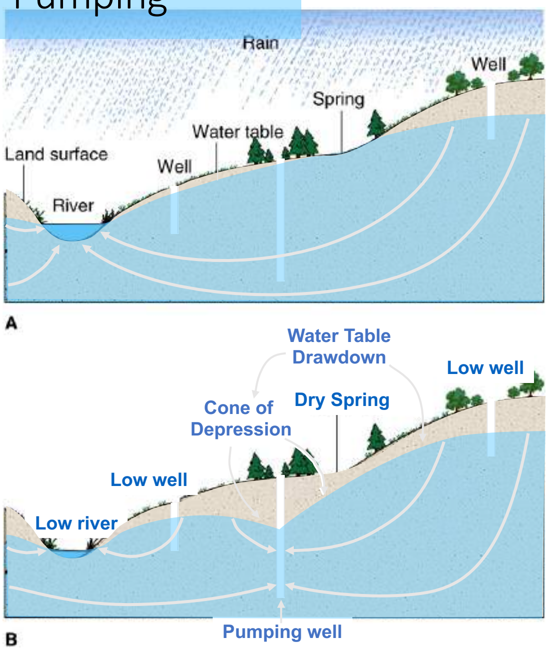
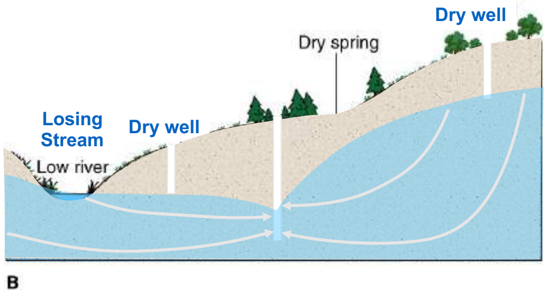
Effects of Short-term Pumping

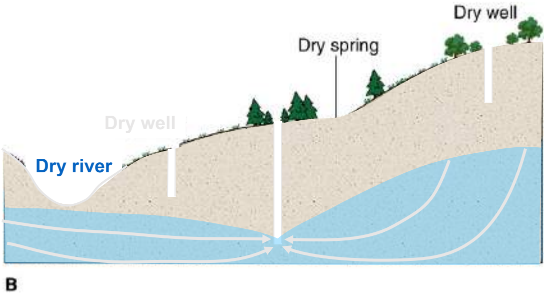
- Change in flow regime
- Loss in hydraulic gradient
- Low flow in rivers/streams
- Temporary drying of springs and well



22

Effects of long-term Pumping





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Ground Water - Indian Scenario

- India is the largest user of Ground Water in the world
    - ✓249 billion cubic meter (BCM) per year
    - ✓25% of global withdrawals
    - ✓More than the ground water extraction of USA & China combined.
- Nearly 60% of irrigation requirements met from from ground water
- Nearly 85% of rural and 50% of urban drinking water supply met from ground water
- Increasing dependence on ground water has resulted in over-exploitation- leading to dwindling well yield and declining water levels

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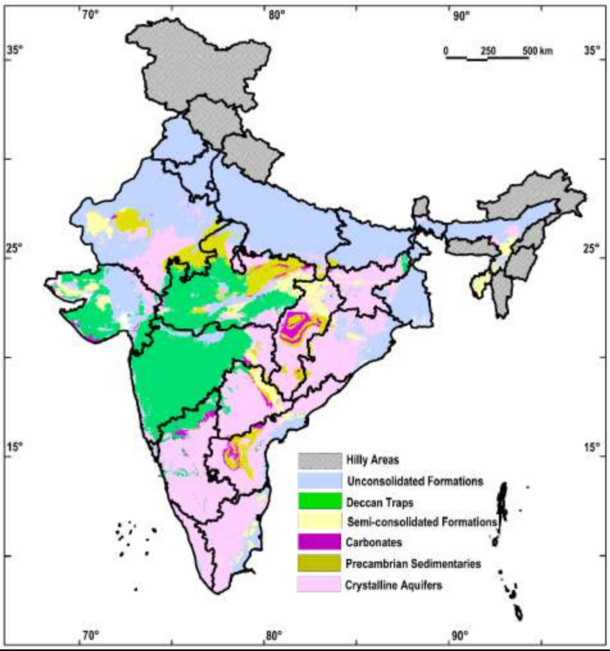
Principal Aquifer Systems of India

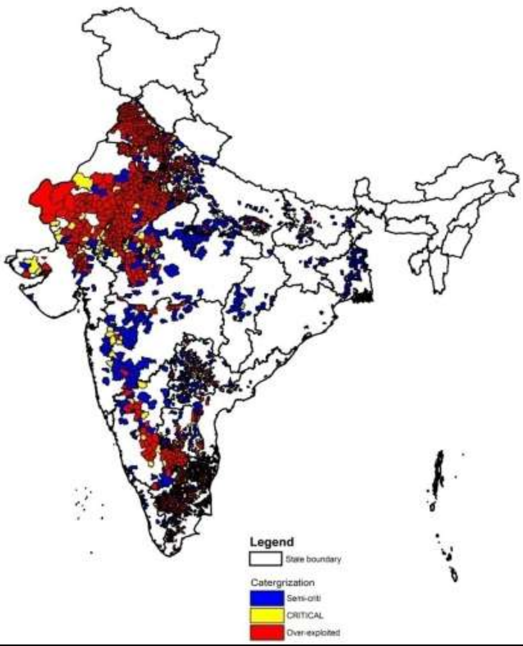


Alluvial aquifers along the Indo-Ganga-Bramhaputra plains are highly potential.

Hard rock aquifers occupying nearly 70% have low to moderate potential.

25

Categorization of Groundwater Assessment Units of India



More than 20% of the assessment units are categorized as either ***over-exploited*** or ***critical***

Nearly 90% of ground water withdrawal is for irrigation purposes.

Assessed units	6881
Over-Exploited	1186 (17%)
Critical	313 (4.5%)
Semi-Critical	972 (14%)
Safe	4310 (63%)
Saline	100 (1.5%)

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Groundwater Quality

- Ground water in major part of the country is potable.
- Major contaminations reported are Arsenic, Fluoride, Salinity, Iron and Nitrate
  - Arsenic contamination has been reported mostly from the Indo-Ganga-Bramhaputra Alluvial plains.
  - Fluoride contamination is most prevalent in north-western part and the southern peninsula.
  - Ground water salinity can be attributed mostly to the following two reasons: Inland salinity (north western India) and sea water ingress (Gujarat coast and the eastern coastal plains).
  - Nitrate is the most prevalent man-made ground water contamination reported from shallow aquifers in several parts of the country.

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THANK YOU

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An Overview of Mineral Exploration and Deposit Modelling

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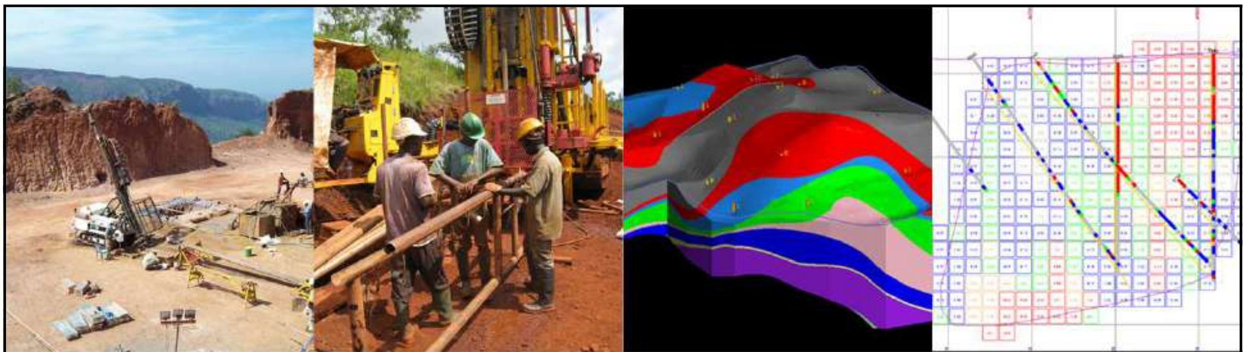

An Overview of Mineral Exploration and Deposit Modelling

Presented By: Shameek Chattopadhyay, Director and Principal Consultant (Resource Geology), SRK Consulting

For: The Undergraduate 1st Year and 2nd Year Students of IIT, Kanpur

Date: 23rd November 2020

2

Fundamentals of Mineral Exploration

3

Civilization and Minerals

- Minerals and metals are essential components for the growth of human civilization and society.
- The use of mineral can be dated back to pre-historic age.
  - Copper age – 6000 BC
- Industrial Revolution in Europe started in 1800s and caused exponential demand of minerals
- Are these minerals abundant in the earth's crust and readily available for extraction?

Steel

Aluminium Foil

Cement

Jewellery

Hematite
Fe_2O_3

Bauxite
$Al_2O_3.2H_2O$

Limestone
CaO3

Native Gold
Au

4

4

What is a Mineral Deposit?

When a useful element is sufficiently concentrated in an accessible part of the Earth's crust so that it can be profitably extracted it is called a Mineral Deposit.

	Average crustal abundance	Typical exploitable grade	Approximate concentration factor
Al	8.2%	30%	×4
Fe	5.6%	50%	×9
Cu	55 ppm	1%	×180
Ni	75 ppm	1%	×130
Zn	70 ppm	5%	×700
Sn	2 ppm	0.5%	×2500
Au	4 ppb	5 g t^{-1}	×1250
Pt	5 ppb	5 g t^{-1}	×1000

Source: Robb 2003

There must be some geological processes that enable enrichment of these elements.

- Igneous Processes
- Hydrothermal Processed
- Sedimentary Processes
- Surficial Processes

5

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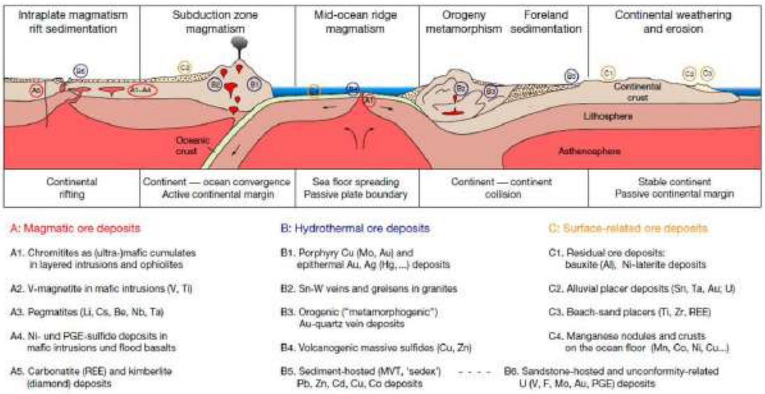
Where to Find Mineral Deposits?

If you want to find elephants, go to elephant the country.



After Heinrich 2014

There must be a series of activities that enable understanding of the geometry, shape, continuity, variability, mineralogy, and other factors that has impact on the extractability of these elements.

6

What is Mineral Exploration?

Mineral exploration is the search for materials in the earth's crust that appear in high enough concentrations and amounts to be extracted and processed for profit.

It also aims to discover deposits of minerals and rocks that can be used to meet the resource needs of society.

It is also carried out to replace the ore deposit being mined currently and or increase the company's ore reserve.

Photo Courtesy – SRK Consulting

7

Type of Discoveries

Greenfield Discoveries

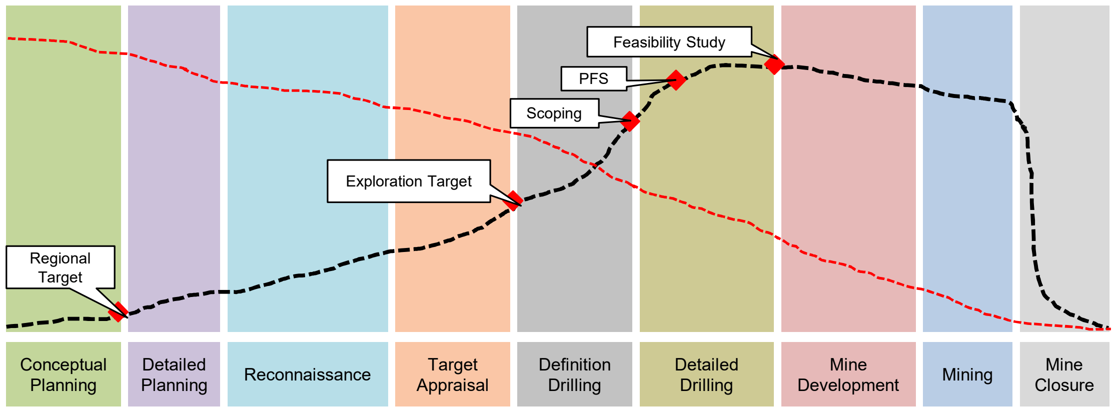
- The term comes from the building industry – where undeveloped land is described as Greenfield.
- Findings from a broad base grassroots exploration programme well away from known orebodies or known mineralised belts.
- Pioneering discoveries in new locales.
- Example – Broken Hill (Australia) 1883

Brownfield Discoveries

- The term comes from the building industry - where previously developed land is described as Brownfield.
- Discovery is made by enhancing the reserve in strike and dip continuity of known orebody or in the vicinity of an existing mine.
- Economics of development are improved by existing infrastructures.
- Example - Rampura-Agucha (India) 1977

8

Stages of Exploration



Modified from Eimon 1988 and Moon 2013 Risk Expenditure

9

9

Mineral Exploration Tools

10

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Exploration Tools

- Surface Indication and Ancient Mining
- Geological Mapping
- Exploration Geophysics
- Exploration Geochemistry
- Drilling, Logging, Sampling and Assay

Photo Courtesy – SRK Consulting

11

Surface Signatures

- **Favourable Geological Formation**
  Ultramafic Rocks in Sukinda Valley (India) for Chromite Exploration
- **Weathering**
  Presence of gossans above Rajpura-Dariba zinc-lead-silver deposit (India)
- **Ancient Mining and Smelting**
  Zawar Mine, zinc-lead-silver deposit (India)
- **Shear Zone**
  Copper sulfide veins in Surda Copper Deposit (India)
- **Lineament**
  Aravalli Mountain, India (India)

12

Geological Mapping

A geological map is a record of geological facts such as occurrence of rocks in space and their contacts, weathering effects such as leaching or gossan, and structure in their correct space relations.

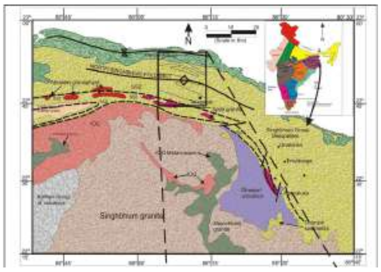
Surface Geological Map

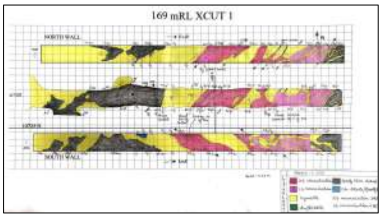
Underground Geological Map

Regional Scale (1:50,000 – 1:25,000)

District Scale (1:50,000 – 1:25,000)

Deposit Scale (1:5000-1:500)





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Remote Sensing

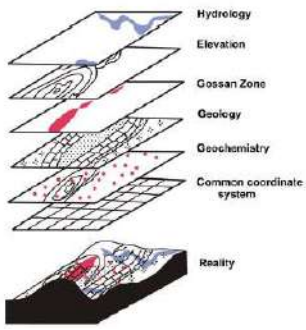
Remote sensing is the process of detecting and monitoring the physical characteristics of an area by measuring its reflected and emitted radiation at a distance (typically from satellite or aircraft). Special cameras collect remotely sensed images, which help researchers "sense" things about the Earth.

Integration of multilayer data and overlay for multidisciplinary interpretation

Application in Mineral Exploration

Recognizing hydrothermally altered rocks by their spectral signature

The mapping and analysis of the geology, faults and fractures of an ore deposit



Reference – Halder 2013

14

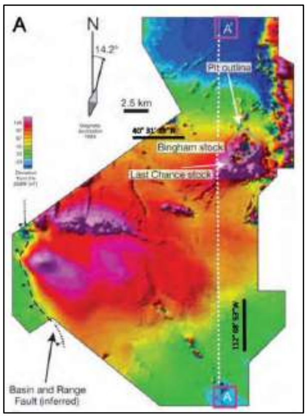
Exploration Geophyics

Exploration Geophyics involves acquisition and interpretation of the physical properties of rocks to determine the subsurface geology.

Method	Application	Examples
Gravimetric	Ground, marine	Heavy minerals deposits, iron ores
Magnetic	Ground, marine, airborne, drill-hole logging	Iron ores, magnetite, pyrrhotite, black sands, kimberlites, chromite ores,
Electrical: Resistivity	Ground, marine, drill-hole logging	Sulfide deposits, massive sulfides, base metals
Radioactive	Ground, airborne, drill-hole logging	Radioactive minerals: uranium, thorium, potassium; coal
Seismic	Ground, marine	Coal, uranium, heavy minerals, buried placer deposits

Integration of geological and geophysical data is the key to the right interpretation.

Aeromagnetic Map over Bingham Porphyry Copper System



Steinberger et al. (2013)

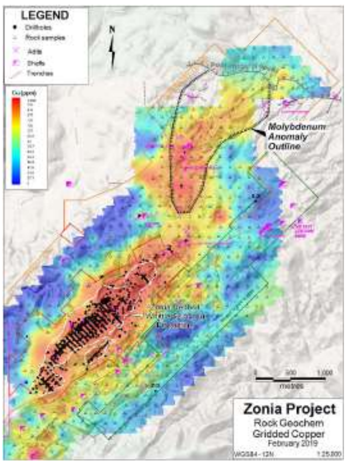
15

Exploration Geochemistry

fundamentally deals with the enrichment or depletion of certain chemical elements in the vicinity of mineral deposits other than barren regions.

Each deposits, there are central zone or core where valuable elements/minerals are concentrated. The zone surrounding the core deposit is known as halo or anomaly. The analysis of pathfinder elements show the path of mineralization discoveries.

Geochemistry is a important component of mineral exploration as major all deposits are low grade with high tonnage. Discovery is highly dependent on geochemical analysis.



16

Drilling

Drilling is used for obtaining detailed information about rock types, mineral content, rock fabric, and the relationship between the rock layers close to the surface and at depth.

- Rotary
- Percussive
- Auger
- Reverse Circulation
- Diamond Core

Typically low quality and used for reconnaissance exploration.

Typically high quality and used for definition drilling.

Drilling is the most expensive activity in mineral exploration and therefore warrants careful planning after integrating all surface exploration data

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Geological Logs

Geological Log is a written and/or graphic record of the geologic data obtained from drillhole core and/or cuttings.

- Recovery
- Geotechnical
- Lithology
- Alteration
- Mineralisation
- Structural

Obtaining core is expensive so it is sensible to retain it for future examination.

Core Photography provides excellent platform for digital archiving and future reference for fresh geological appraisal

Photo Courtesy – SRK Consulting

18

Sampling

Sampling is a scientific, selective process applied to a large mass or group (a population, as defined by the investigator) in order to reduce its bulk for interpretation purposes.

This is achieved by identifying a component part (a sample) which reflects the characteristics of the parent population within acceptable limits of accuracy, precision, and cost effectiveness.

In the minerals industry the average grade of a tonnage of mineralized rock (the population) is estimated by taking samples which are either a few kilograms or tonnes in weight. These samples are reduced to a few grams (the assay portion) which are analyzed for elements of interest.

Photo Courtesy – SRK Consulting

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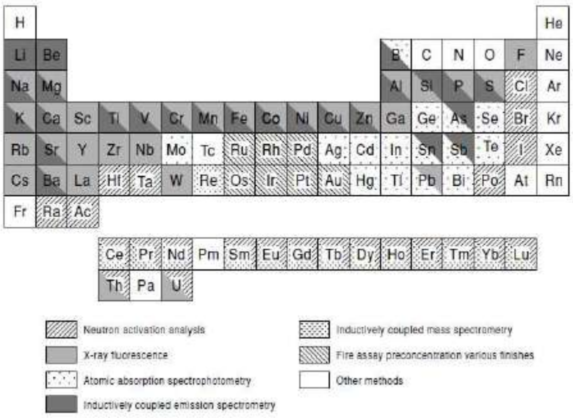
Assay

Assay is a process for the determination of concentration of certain element in ore.

Method	Multielement	Precision	Sample Type
Calorimetry	No	Poor	Solution
AAS	No	Good	Solution
XRF	Yes	Good	Solid
ICP-ES	Yes	Good	Solution
ICP-MS	Yes	Good	Solution

The choice of analytical method should aim at optimizing the main target element through an understanding of mineralogy.



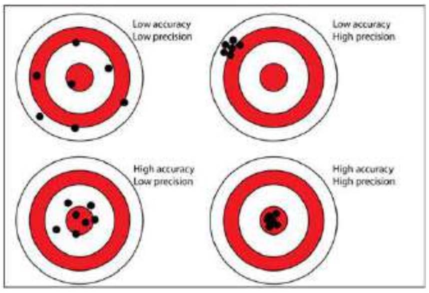
After Moon 2013

20

Quality Assurance and Quality Control

Quality Control (QC) – measures that are included in each assay run to ensure that the analytical test has been successfully competed

Quality Assurance (QA) – the overall program / procedures in place to ensure that the final results reported by the laboratory are correct including reporting.



Potential Error Sources	Control Measures
Sampling Errors	Field Duplicate
Contamination	Blank
Sample ID Errors	Blank
Accuracy of Assay Results	Standard/CRM
Precision of Assay Results	Pulp Duplicate
Laboratory Performances	Check Samples in Umpire Laboratory

Identify the potential sources

Analyse, Improve and Control

21

Deposit Modelling

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Workflow of Deposit Modelling

Understanding of Geology and Controls of Mineralisation → Data Quality Assessment → Data Validation → Geological Modelling → Domaining

↓

Compositing → High/Outlier Grade Capping (If Required) → Statistical Analysis → Geostatistical Analysis → Search Neighbourhood Analysis

↓

Selection of Appropriate Estimation Method → Model Validation → Mineral Resource Classification → Assessment of the *"reasonable prospect for eventual economic extraction"* → Mineral Resource Statement

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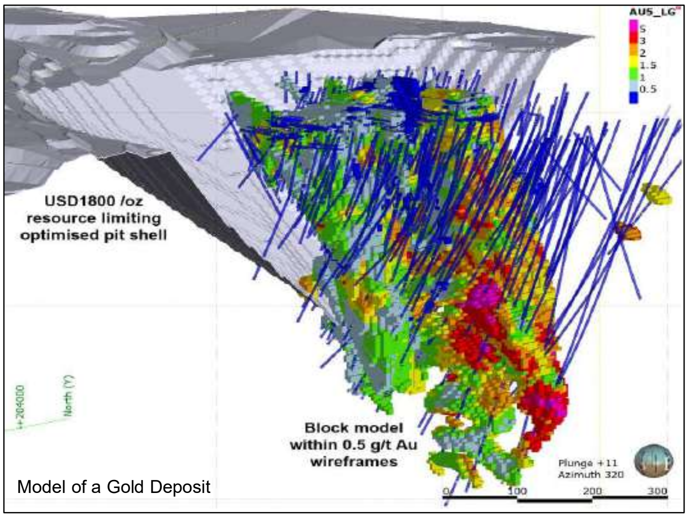
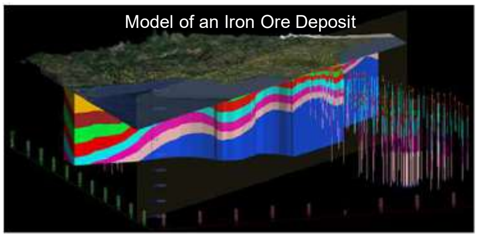
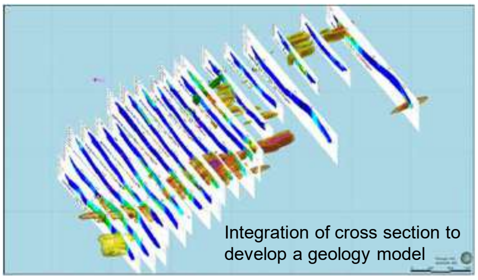
Example of Deposit Modelling



Model of a Gold Deposit


Model of an Iron Ore Deposit


Integration of cross section to develop a geology model

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Reporting

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Stakeholders of Geological Reports

- Geologists/ Engineers – Further Exploration Planning/Engineering Decisions
- Company Management – For better visibility of future business cases and opportunities
- Banks/Investors – Investment Decisions/Valuation
- Government – Maintaining National Inventory/Regulation/Policy Decision

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Guiding Principles

Globally efforts are being made for harmonization of terminologies

CRIRSCO Type Public Reporting Codes for Stock Exchange Listing and Fund Raising
JORC 2012 – Australasia
NI 43-101 – Canada
SAMREC – South Africa

United Nation's Framework Classification System

Other Rule Based Codes
GKZ System (Former Soviet Union)
Indian Standard Practice for Coal

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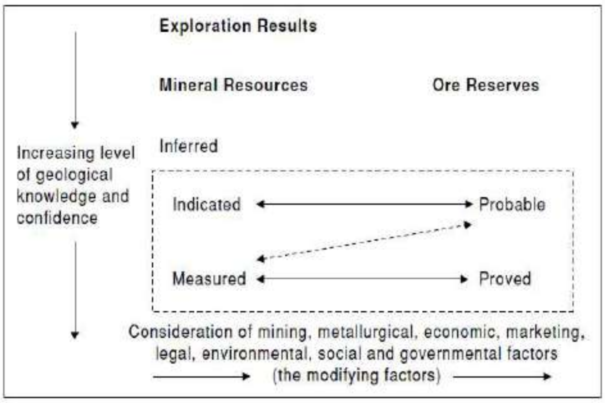
Reporting Principles



Reports should be based on the principles of Transparency, Materiality and Competency

Exploration Results must be presented with sufficient caution – reflecting the uncertainties

Resource and Reserve must not be added together

Mineral Resource Classification and Reporting requires sufficient relevant experience and detailed understanding on the style of mineralization, nature of deposit and activities undertaken.

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Concluding Remarks

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Concluding Remarks

- Mineral Exploration is a time consuming and financially risky activity.
- It involves a series of geological tasks, involving geology, geophysics, geochemistry and several other applied sciences.
- Deposit Modelling can be complicated. A thorough understanding of the geology and data generation processes are essential to undertake deposit modelling.
- Mineral Resource Classification and Reporting requires sufficient relevant experience and detailed understanding on the style of mineralization, nature of deposit and activities undertaken.

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Thank you for your attention

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Overview of general and basic petroleum geosciences

Suman Das, PhD
Explorationist, Schlumberger

1

Journey from Geology to Geophysics to Geoscience

Senior Explorationist (2019-date)
(Schlumberger, Houston)

M.Tech (Applied Geology) 2001-2003
IIT Kharagpur
PhD. (Metamorphic petrology and structural geology) (2003-07)
IIT Kharagpur, India, University of Kiel, Germany

Senior Geophysicist (2013-2019)
(Schlumberger, India)

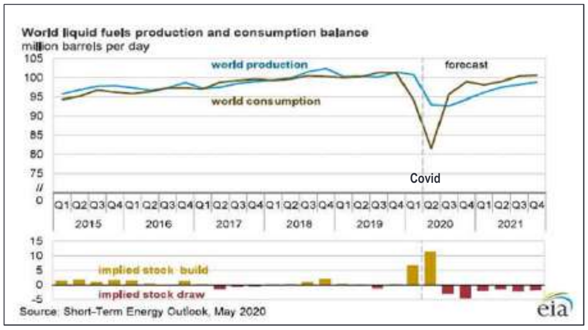
Regional Geologist (2007-2013)
(Reliance Industries Limited)

M.sc (Geology) 1999-2001
Jadavpur University

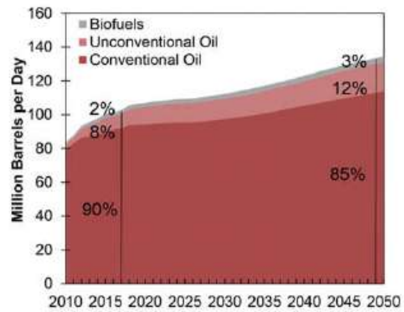
Schlumberger-Private

2

Production vs consumption



Source: Oil and Gas journal, May 12th, 2020



Source: Center for sustainable systems, University of Michigan

Conventional Resources are concentrations of oil or gas that occur in discrete accumulations or pools. Rock formations hosting these pools traditionally have high porosity and permeability and are found below impermeable rock formations. These impervious layers form barriers to hydrocarbon migration resulting in oil and gas being trapped below them. Conventional oil and gas pools are developed using vertical well bores and using minimal stimulation.

Unconventional Resources are oil or gas-bearing units where the permeability and porosity are so low that the resource cannot be extracted economically through a vertical well bore and instead requires a horizontal well bore followed by multistage hydraulic fracturing to achieve economic production.

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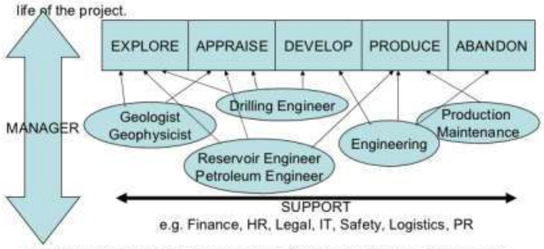
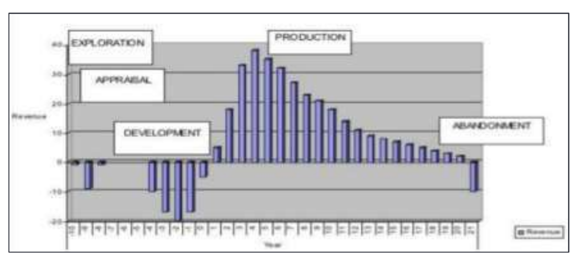
Technical experts involved during different life cycle

Each stage of the life cycle requires different professional inputs. Below is the multi-disciplinary approach adopted by most companies at all stages during the life of the project.



The support functions of Finance, HR, IT, Safety, Logistics and Government Relations would be fully involved in the making of key decisions.



Revenue vs Time during life cycle

Source: www.inwellflowsol.com

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Treasure hunt

Area

A plan

Clue

Eliminate wrong path

Reaching box

Find out the magic box

Open the box to find out its treasure or water bottle

Evaluate and count

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Exploration cycle

Area
Block

A plan
Project plan

Clue
Domains

Eliminate wrong path
Risking and ranking

Reaching box
Drilling location

Find out the magic box
Prospect

Open the box to find out its treasure or water bottle
Appraisal and developemnt

Evaluate and count
Production

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The journey of hydrocarbon hunt

	Exploration	Appraisal	Development	Production
	Gravity magnetic data	Gravity magnetic data	Gravity magnetic data	Gravity magnetic data
C L U E S	Seismic data	Seismic data (Re-processing)	Seismic data (Re-processing)	Seismic data (4D seismic)
		Well data	More Well data	More Well data
			Detail analysis from well and seismic	Detail analysis from well and seismic

Cost

Uncertainty

It is important to evaluate the cost with the reduction of uncertainty

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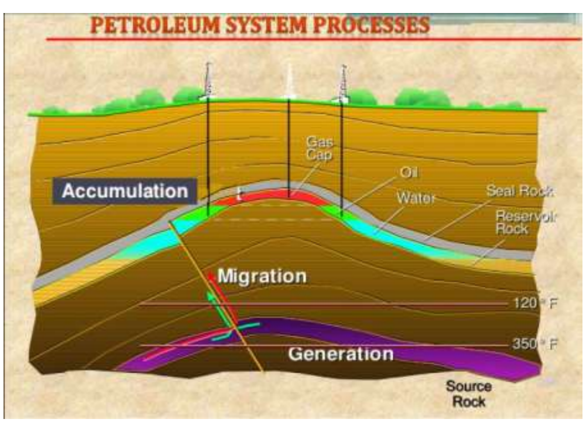
Petroleum system elements



What do we try to understand

- Source presence (PSM)
- Distribution of reservoir (Presence) (Well calibrated Seismic attribute)
- Reservoir quality (Well calibrated seismic attribute)
- Trap (structural\stratigraphic) (Structural interpretation+attribute)
- Migration (PSM+Fault interpretation)

At any stage, information from seismic is important because of its lateral coverage

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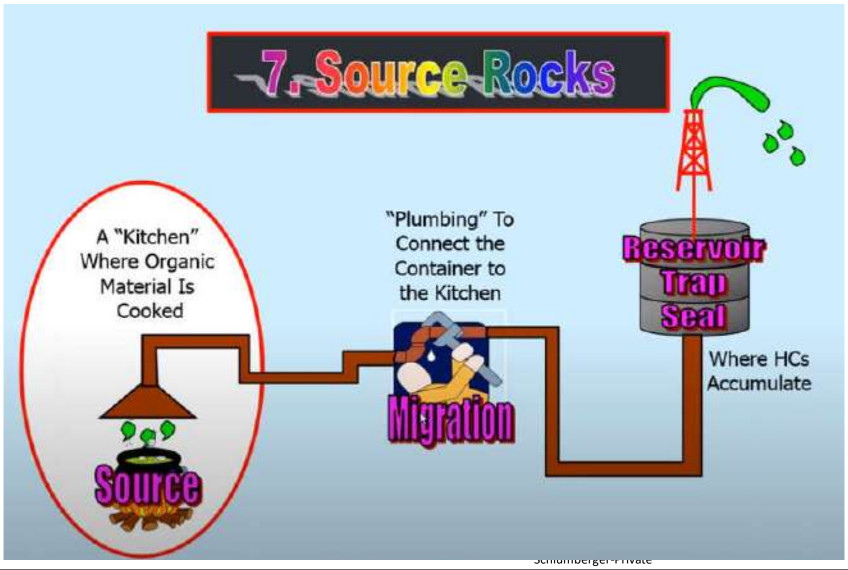

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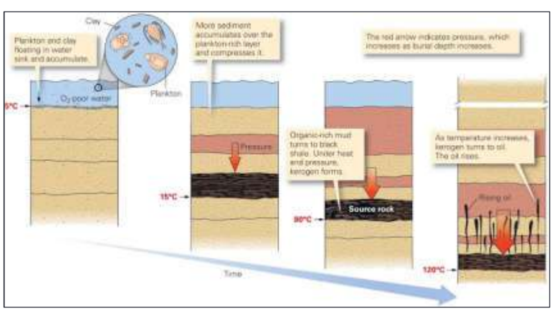
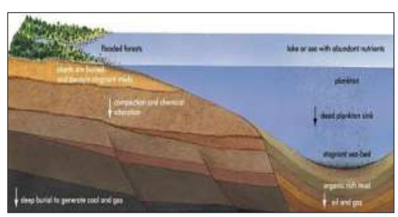
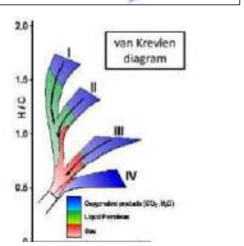
Source rock

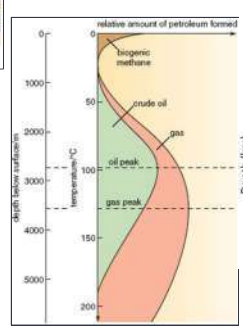


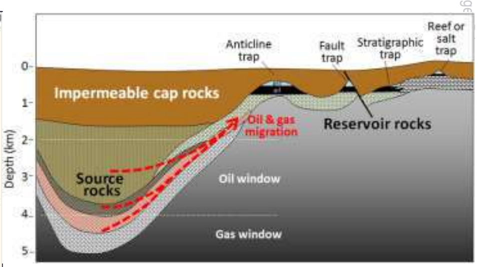


➤ Kerogen Types and hydocarbon potential

Kerogen type	Origin	HC potential
I	Algal bodies	Very good for oil
II	Planktons	Good for oil and gas
III	Higher Green plants	Good for gas
IV	Oxidized woody debris	Largely inert







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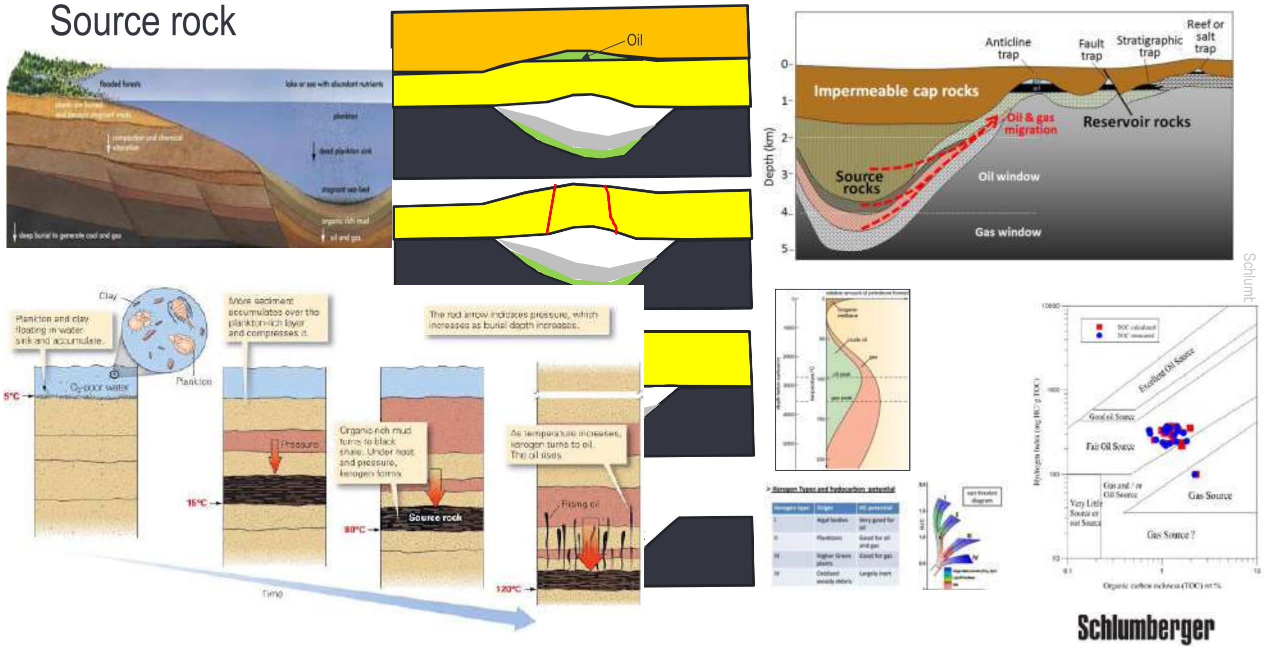
Source rock



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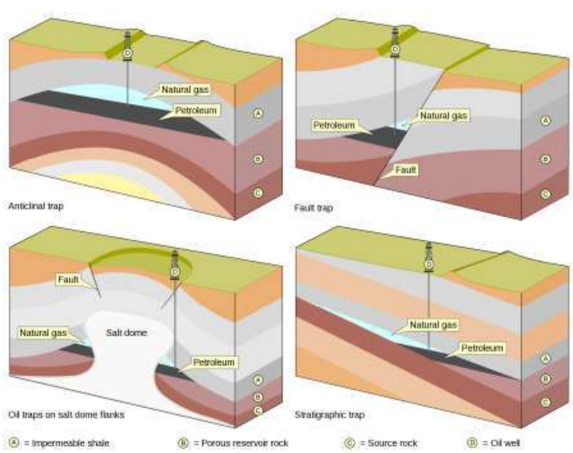
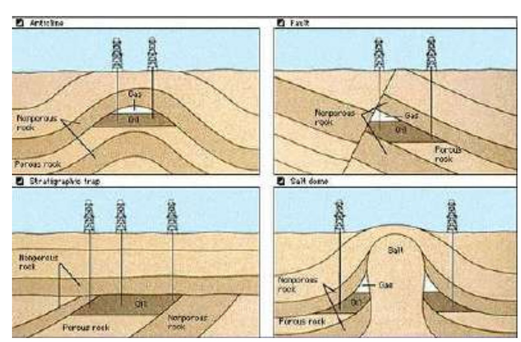
Trap

Trap is the container which can hold Hydrocarbon. This can be structural (anticline\ fault bound etc.) and stratigraphic





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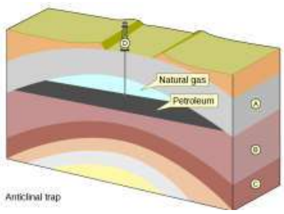
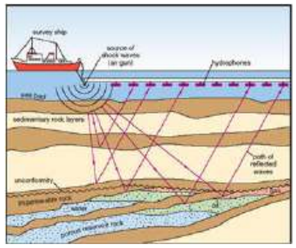
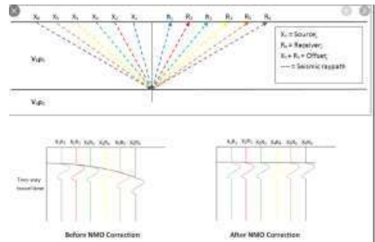
How we know about Trap

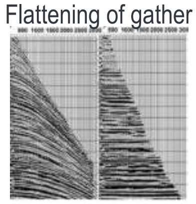


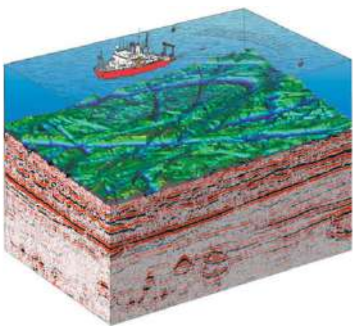


NMO correction

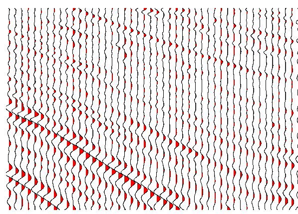


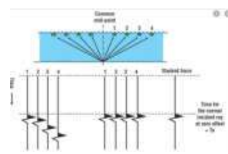
Flattening of gather





Stacked Seismic





Stacked trace

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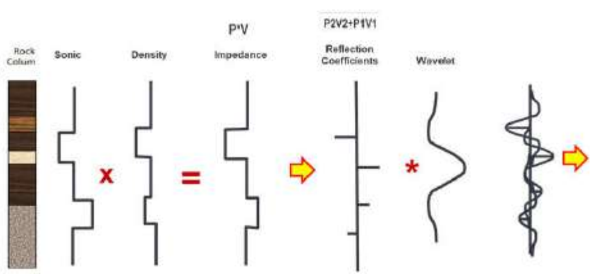
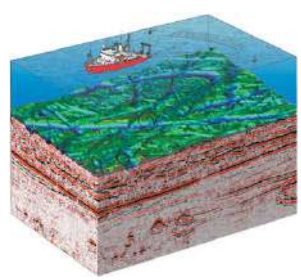
The seismic trace is reflection of lithology boundary





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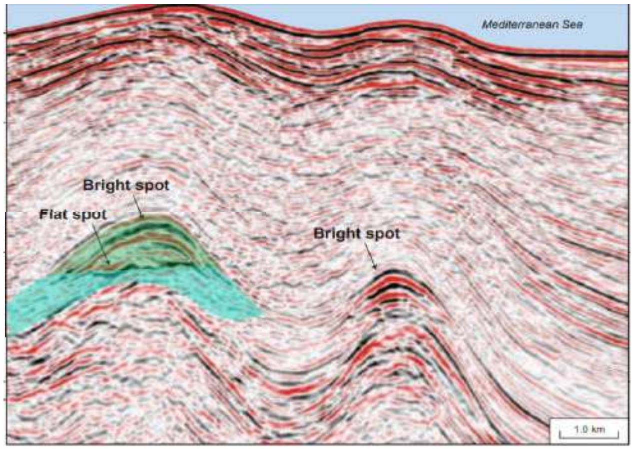
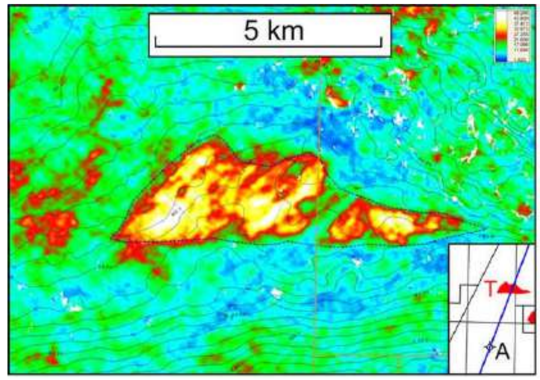
Simple way to look into seismic anomaly to understand possible fluid effect





Paleocene trap west of Shetland, N. Loizou, 2014

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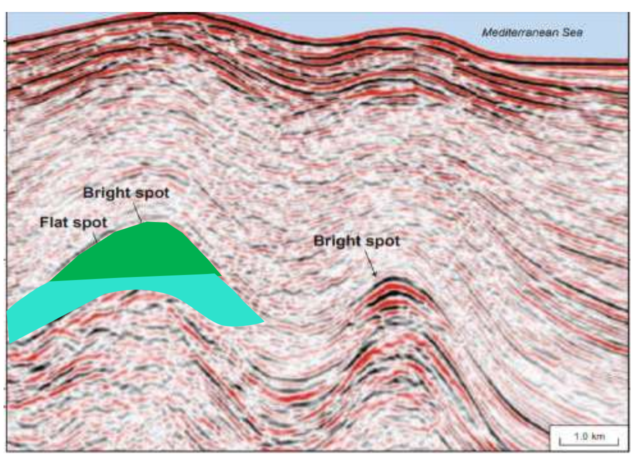

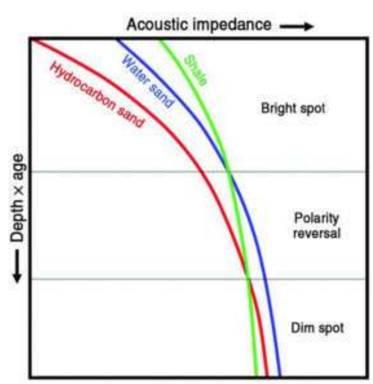

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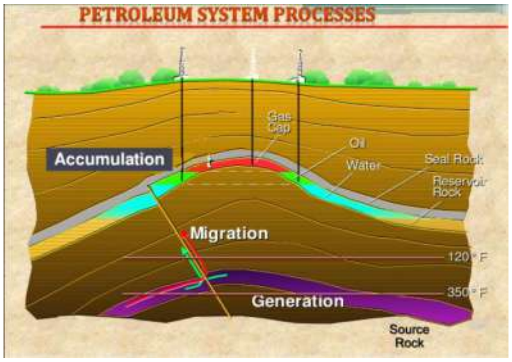
Who are involved before drilling a well (exploration)



Geologist

Geophysicist

Petroleum system analyst

Seismic Interpreter

Structural Geologist

Seismic inversion specialist

Sedimentologist

Petrophysicist

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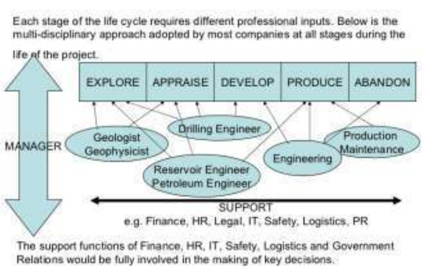
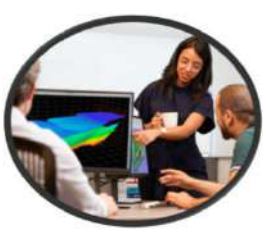
What's next? Drilling a well





Reservoir Engineer

Drilling Engineer

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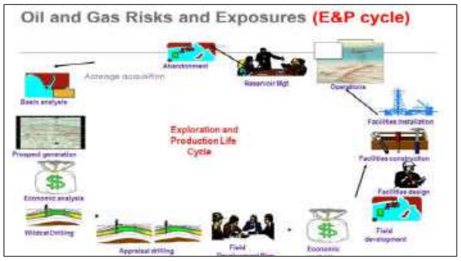
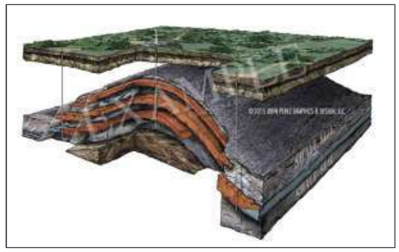
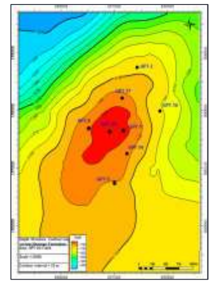
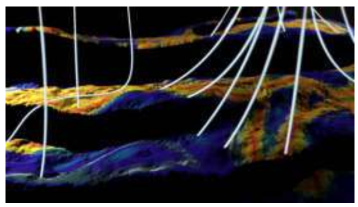
Appraisal and development









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Integration of key

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Thank you

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