PHY317: Physics of Solid Earth

Course Outline and Schedule

Origin, shape, structure, and major deviations of the earth. The Earth's main magnetic field and its distribution. Electrical theory of the Earth's core and origin of the magnetic field, seafloor spreading, continental drift and plate tectonics.

Prerequisite	High school knowledge of Physics and Mathematics
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Grades	The final grade is calculated on an absolute scale. There are **100 points** possible for this course of which **30 points** are for continuous assessments and **70 points** for the final examination.
Classes	The University of Abuja (UofA) provides online tools. Hence this course will be online in most cases. Please remember to activate your UofA email address.
Information Dissemination	For up-to-date information about this course please join the WhatsApp group of the class. Register on the lecturer's record of students for this course by using the link (to be provided in the WhatsApp group) to fill a form

Course Introduction

Geophysics is a unit in the University of Abuja's department of Physics that offers an opportunity for specialty as an area of research interest. This course introduces the origins, shape and composition of the Earth. The course also attempts to review the various forces at play to keep the Earth in dynamic equilibrium during its evolution within the universe. The continuous structural changes on the surface of the Earth due partly to the mechanics, electrodynamics and thermal behaviour of the earth are considered. Geophysical techniques provide ways to image the subsurface after some analysis based on measurements on/above the surface of the Earth, the Moon or other planets. This course is expected to provide foundational knowledge for a career in geophysical investigation of the Earth.

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1. Origin and Shape of the Earth

Centuries of studying Earth, its neighboring planets, and meteorites have enabled the development of models of the birth of the Solar System. According to science, the universe comprises of several *galaxies* and our *solar system* is part of *The Milky Way Galaxy* which is disk-shaped comprising billions of stars with varying sizes. Our solar system consists of 8 planets– *Mercury*, *Venus*, *Earth*, *Mars*, *Jupiter*, *Saturn*, *Uranus* and *Neptune* (excluding *Pluto*), 31 satellites and a belt of asteroids. The Earth is one of the 8 planets that orbit the sun in our solar system. The earth exists in three states of matter– solid, liquid and gas.

1.1 Theories About Earth's Origin

According to the *Big Bang theory*, the universe blinked violently into existence 13.77 billion years ago (Figure 1). The Big Bang is often described as an explosion but imagining it as an enormous fireball is not accurate. The Big Bang involved a sudden expansion of matter, energy, and space from a single point. The kind of Hollywood explosion that might come to mind involves expansion of matter and energy within space, but during the big bang, space itself was created.

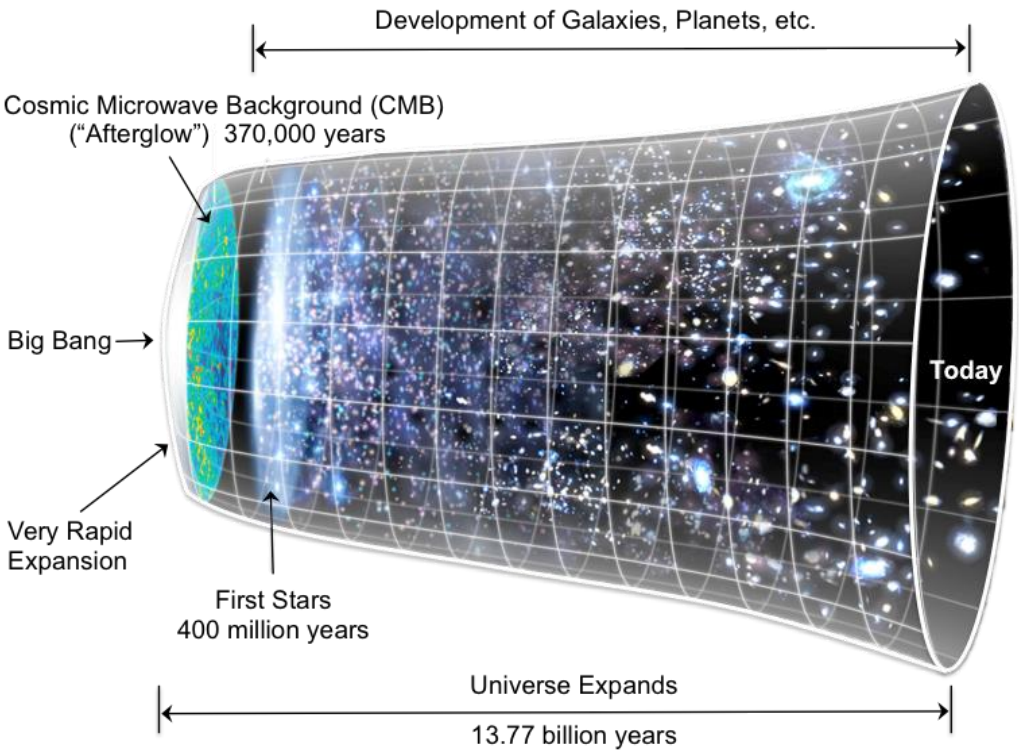

Figure 1 The Big Bang and development of the universe (Steven Earle, "Physical Geology")

Some suggestions as to the birth of our planet may be found in a study of its relations to the other bodies of the solar system, and in its characteristics as a member of that system. Broadly speaking, two theories explained the formation of the earth and other planets.

(a) The Cold Origin Theory (*Nebular hypothesis*);

(b) The Hot Origin Theory (*Planetismal and Gaseous tidal hypotheses*).

1.1.1 Nebular hypothesis (Kant and Laplace, 1755): Cold Origin

This hypothesis suggests that the solar system was formed through the condensation of a *nebula* (a primeval rotating cloud of dust and gas which had a diameter of more than 9×10^9 km). The denser centre of the rotating dust in the Nebula's hypothesis formed the sun. The outer planets were the first to be formed, followed by Mars, Earth, Venus, and Mercury. This hypothesis suggests a sequential origin from outermost planet to innermost. During the past, the entire solar systems existed as a hot gaseous mass called nebula rotating in space. With time, the gaseous mass (nebula) cooled and contracted. Due to contraction, there developed a bulge at the equatorial region. This bulge subsequently separated into several rings. The ring coalesces in the form of a globe and continues to revolve around the nebula. In similar manner, ten rings were formed. Nine of them became planets. The last one broke down into smaller fragments to form the group of planetoids, while the remnant of the pre-existing nebula formed the central incandescent mass of the solar system (the Sun). However, this theory failed to explain angular momentum observation in the solar system whereby sun alone constitutes 99.9% mass of the solar system but 99% of the angular momentum of the solar system is concentrated in the large farther planets from the sun.

This hypothesis suggest that earth was originally a globe of very hot vapor that cooled, contracted, and gave off a ring which went through some process and became the moon. The parent mass continued to cool and shrink until it became liquid, and finally formed a crust over its outer surface, the interior remaining very hot. At this early stage of the earth's history the atmosphere contained all of the gases which now compose it, great quantities of gases that are united with other elements as parts of rocks, and all of the hydrogen and oxygen that are in the waters of the planet. When the cooling process had gone on for so long that gases formerly in the atmosphere could stay in the earth, and those falling as water could remain upon it instead of passing back as vapor, the ancestors of our present oceans began to form. (Fenton, 1921).

1.1.2 Planetismal hypothesis (Chamberlain and Moulton, 1905): Hot Origin

Planets were formed as a result of mutual interaction between the sun and another star of suitable size. This is the *theory of biparental origin of the solar system.* This theory postulates that

due to the near approach of a larger star, tidal distortions were raised upon the surface of the sun and these, in conjunction with the eruptive force prevalent in the sun (known as the *solar prominence*) brought about a description of the mass of the sun and a number of gaseous bulbs were shot forth, in space, to great distances. These gaseous solar materials thus ejected in space were subjected to immediate chilling, resulting in the formation of a number of minute solid particles known as *planetisimals*. These planetisimals continued to rotate round the sun in highly elliptical orbits. The orbits must have happened to intersect one another and at points of intersection, they must have collided whereby the small planetisimals continued to coalesce gradually giving rise to the planets. During collision and coalescence of the planetisimals, large quantities of heat must have been generated and were dissipated in space before the next collision could occur. Accordingly, the planets must have been solid all the time during the growth. This theory accepts that the collision must have taken place in quick succession and accumulation of heat might have caused a melting of the masses of the planets.

1.1.3 Gaseous tidal hypothesis (Jeans and Jeffreys, 1925): Hot Origin

This also accepts the idea of biparental origin like that of the planetisimal hypothesis but refuses to consider the disruptive forces in the sun (i.e., the solar prominence. According to Jeans and Jeffreys, during the ancient past, an extremely large star, while moving in space chanced to approach the sun. Due to progressive and nearer approach of the star, a tidal pull was raised on the surface of the sun and this increased in size with the nearer approach of the passing star. At the stage, where the passing star began to recede, the tidal pull on the surface of the sun, thus formed, was detached from the body of the sun in the shape of a spindle bulging near the centre and tapering at both ends. This very large mass of gas, thus ejected in space, was naturally extremely unstable and was immediately broken down into a number of small fragments. In all, ten such pieces were formed, nine giving rise to the planets and one, which was broken down into pieces, to the group of planetoids. These fragments formed into globular masses revolving round the sun along definite orbits and cooled down gradually from the gaseous to the liquid and ultimately to the solid state.

The hot origin hypotheses are popular but also suffer from some weaknesses which include:

- Failure to explain angular momentum observation about the solar system;
- Unlikelihood that the collisions happened only once and never again;
- Why the collision is perfectly elastic? The materials could have scattered.

1.2 How did life begin?

In The Origin of Species, Charles Darwin (1859) hypothesized that new species arise by the modification of existing ones. Scientists have toiled to create life from sparks and gasses in the

laboratory to illuminate how life first formed in Earth's early conditions. But even pinning down what those early conditions were remains an elusive goal. From what materials did life originate? Did life, as Darwin speculated, originate in a "warm little pond," perhaps a tidal pool repeatedly dried and refreshed? Or might life be rooted among hydrothermal vents? Could life's origins even lie beyond Earth? Developing an accurate picture of the physical environments and the chemical building blocks available to early life is a critical Earth science challenge. Clues to shed light on these mysteries stem largely from investigations of Earth's ancient rocks and minerals—the only remaining evidence of the time when Earth's life first emerged.

[Origin and Evolution of Earth 2008 The National Academy of Sciences]

1.3 Peculiar Features of the Earth

The Earth possesses some distinguishing features different from other planets. Some of the features suit the development of life. Some of the characteristics are:

- high gravitational field, that keeps objects on its surface
- uniform motion such as rotation, revolution and wobbling that causes day and night and seasonal changes
- the presence of enough water for activities such as agriculture
- balanced distance from the sun, not too short nor too far
- the presence of rich atmosphere in gaseous form and contains ozone layer

1.4 Age of the Earth

The exact age of the earth is not known, but it is thought to be at least *4.5 billion years*. Scientists have been able to determine the probable age of the Solar System and to calculate an age for the Earth by assuming that the Earth and the rest of the solid bodies in the Solar System formed at the same time and are, therefore, of the same age. The ages of Earth and Moon rocks and of meteorites are measured by the decay of long-lived *radioactive isotopes* of elements that occur naturally in rocks and minerals that decay with half-lives of 700 million to more than 100 billion years to stable isotopes of other elements. These dating techniques known as *radiometric dating* are used to measure the last time that the rock being dated was either melted or disturbed sufficiently to re-homogenize its radioactive elements.

Rocks and fossils (the remains of plants and animals preserved in the rocks) can be dated by measuring the decay rate of radioactive material that they contain. The number of radioactive particles given off by a substance during a certain time period gives an indication of the age of the substance. Geologic time intervals are measured in millions of years (Table 1). For example, the

dinosaurs became extinct about 70 million years ago. The radius, distance from sun and revolution period of 9 celestial bodies in our solar system are itemized in Table 2.

Over the nearly 5 billion years of earth's history mountains have risen, been eroded away and extreme environmental changes have occurred. For example:

- Palm tree fossils have been found near the North Pole, indicating that a warm climate prevailed there in the geologic past
- Shark teeth have been found hundreds of miles from the nearest modern sea
- Many places that are high and dry today were once covered by seas. In fact, many areas have been covered by seas, uplifted above sea level and submerged again multiple times. Such areas are now called basins

When rivers flow into a large body of water, suspended and dissolved sediments settle to the bottom. The coarsest sediments, such as sand, are deposited first and nearest to the river's mouth. Lighter sediments, such as mud and silt, are deposited farther out and in deeper water. Lime (calcium carbonate), produced by tiny life forms living in warm, shallow water, and is deposited on the water bottom. This deposition of sediments has occurred throughout geologic times that surface water has been present. Deposited sand is compacted and cemented to form sandstone. Lime hardens into limestone. These two sedimentary rock types are the rocks most important to petroleum accumulation and production.

Table 1 Geologic Time Period

Era	**Period**	**Epoch**	
Cenozoic	Quaternary	*Holocene* *Pleistocene*	*today*
	Tertiary	*Pilocene* *Miocene* *Oligocene* *Eocene* *Paleocene*	*1.8 million years ago*
Mesozoic	Cretaceous Jurassic Triassic		*65 million years ago*
Paleozoic	Permian Pennsylvanian Mississippian Devonian Silurian Ordovician Cambrian		*248 million years ago*
Precambrian			*543 million years ago*
			4.5 billion years ago

Table 2 Radius, distance from sun and revolution period of 9 celestial bodies in our solar system

SN	Planet	Radius (km)	Distance from the sun (m.k)	Revolution period (day)
1	Mercury	2439	57.9	88
2	Venus	6052	108.2	245
3	Earth	6378	149.4	365.25
4	Mars	3397	227.9	687
5	Jupiter	71398	778.3	4333
6	Saturn	60000	1427	10743
7	Uranus	23620	2870	30700
8	Neptune	24300	4496.5	60280
9	Pluto	1150	5970	90130

1.5 Sources of Earth's Zoning

After formation the earth warmed up as a result of the following processes:

- **Particle acceleration**: The kinetic energy of the particles coming together turned to heat energy
- **Gravitational pull between the particles**: The pulls resulted in high pressure which raised the heat energy.
- **Radioactivity**: Heat evolved during disintegrations of radioactive elemental components of the earth's particles.

The heat from the above sources raised the temperature of the earth to the melting point of iron which melted the whole earth in an event known as *Iron Catastrophe*.

1.5.1 Zoning of the solid earth

The molten earth that resulted during Iron catastrophe settled such that lighter particles like silicon etc. floated, cooled and formed the outer crust and mantle. The heavier particles like iron etc. settled beneath the crust forming the core. Water containing particle in the earth went through chemical changes and released water which settled on the surface to form the ocean. Gas containing particles also went through chemical changes releasing gasses to form the lightest atmosphere which is located on top of the liquid and parts of the earth.

1.6 Formation of the Oceans

The origin of the oceans may date back to the time of Earth's formation through the accumulation of smaller objects, called planetesimals. Different theories have been presented on the formation of the oceans.

- A popular theory is the gradual accumulation of the atmosphere and the ocean as Earth continues to release gas from its interior. According to this theory, the ocean formed from the

escape of water vapor and other gases from the molten rocks of the Earth to the atmosphere surrounding the cooling planet. After the Earth's surface had cooled to a temperature below the boiling point of water, rain began to fall—and continued to fall for centuries. As the water drained into the great hollows in the Earth's surface, the primeval ocean came into existence. The forces of gravity prevented the water from leaving the planet (https://oceanservice.noaa.gov/facts/why_oceans.html). Volatiles (elements and compounds, including water, that vaporize at low temperatures) were released from the solid phase as the earth accreted. Thus, the earth and its oceans and atmosphere grew together. Liquid water, which is necessary for life continues to exist on the surface of Earth because the planet is at a distance, known as the habitable zone, far enough from the Sun that it does not lose its water to the runaway greenhouse effect, but not so far that low temperatures cause all water on the planet to freeze.

- Another theory is that water and other volatiles were got to the Earth from the outer Solar System later in Earth's history. Although the evidence water was delivered to Earth by impacts from icy planetesimals similar in composition to asteroids in the outer edges of the asteroid belt. Research indicates that hydrogen inside the Earth played a role in the formation of the ocean. This theory may be incorrect because the composition of the ocean offers some clues as to its origin. Examination of water molecules in Comets Halley and Hyakutake suggest that comets cannot have delivered all the water in the earth's oceans. This is because the ice in the comets contains twice as many atoms of deuterium (a heavy isotope of hydrogen) to each atom of ordinary hydrogen as we find in seawater. At the same time, we know that the meteorites could not have delivered all the water, because then the earth's atmosphere would contain nearly 10 times as much xenon (an inert gas) as it does.

The best model for the source of the oceans is a combination of water derived from comets and water that was caught up in the rocky body of the earth as it formed.

Liquid water continues to exist on the surface of Earth because the planet is at a distance, known as the habitable zone, far enough from the Sun that it does not lose its water to the runaway greenhouse effect, but not so far that low temperatures cause all water on the planet to freeze. There are basically three possible sources for the water.

1) water could have separated out from the rocks that make up the bulk of the Earth.
2) water could have arrived as part of a late-accreting veneer of water- rich meteorites, like the carbonaceous chondrites.
3) water could have arrived as part of a late-accreting veneer of icy comets.

1.6.1 Ocean on the surface of the Earth

The water did not all start out on the surface - some of it did because it was delivered by comets, but some started out in the interior and outgassed later. Water is drawn down by subduction in the form of wet and/or hydrated rocks. The oceanic crust is the boundary between the bulk of water and Earth's lithosphere. The oceanic crust has low permeability that may hold water like a bowl of ceramic. The mantle is generally hot and water seeping there would turn to steam and contribute to the gas pressures of the lava wherever it appears. A dynamic process transports water to the surface, rather than just a low permeability that prevents it from seeping down.

Liquid water or water vapor is much less dense than rock and can flow through connected porosity in the earth's crust. In rock at depth, the weight of the overlying rock deforms the rock, collapses pores, and displaces water upwards towards the surface. Water can also dissolve as a solute in molten rock and can be a component of hydrous minerals, these materials are denser than liquid water and could carry water at much greater depths in the earth. However, because we find water at the surface, and because some water is outgassed by volcanos, we know that not all of earth's water is held in the interior.

The Earth is 12,742 km in diameter and the average depth of the oceans is 3.7 km. That means the ocean is very thin in proportion to Earth's massive size. Many natural phenomena can contribute to holding the oceans to Earth's surface. These include ocean water salinity, electromagnetism, electrostatics, surface tension, adhesion, cohesion, atmospheric pressure, subduction, surface irregularities, plant life, and the fact up and down do not exist in space.

1.7 The Earth's Motions

The earth undergoes a series of complex motions to maintain celestial dynamic equilibrium with other planets. The three major motions are:

(a) Rotation about the polar axis (about 24 hours);
(b) Revolution around the Sun (about 365 ¼ days);
(c) Wobble about its equator (The Earth's Orbit Precesses every 25,770 years)

Other identified motions include:

(d) Earth-Moon System Orbits a "Gravitational Centre";
(e) The Sun and Earth Revolve Around the Solar System "Gravitational Centre";
(f) The Sun Revolves Around the Galaxy Once Every 250 Million Years;
(g) The Galaxy is moving through the Universe
(h) Polar Variation (but very small)

As long as you live on the Earth, these motions remain imperceptible.

1.7.1 Earth's rotation about the polar axis

In Figure 2, an imaginary line from the North Pole passes through the center of Earth to the South Pole is the *polar axis*. Earth spins around the polar axis (rotation). A pendulum set in motion will not change its motion, and so the direction of its swinging should not change. However, the pendulum is observed to change direction, given credence to a moving earth. An observer in space will see that Earth requires 23 hours, 56 minutes, and 4 seconds to make one complete rotation on its axis. But because Earth moves around the Sun at the same time that it is rotating, the planet must turn just a little bit more to reach the same place relative to the Sun. Hence the length of a day on Earth is actually 24 hours.

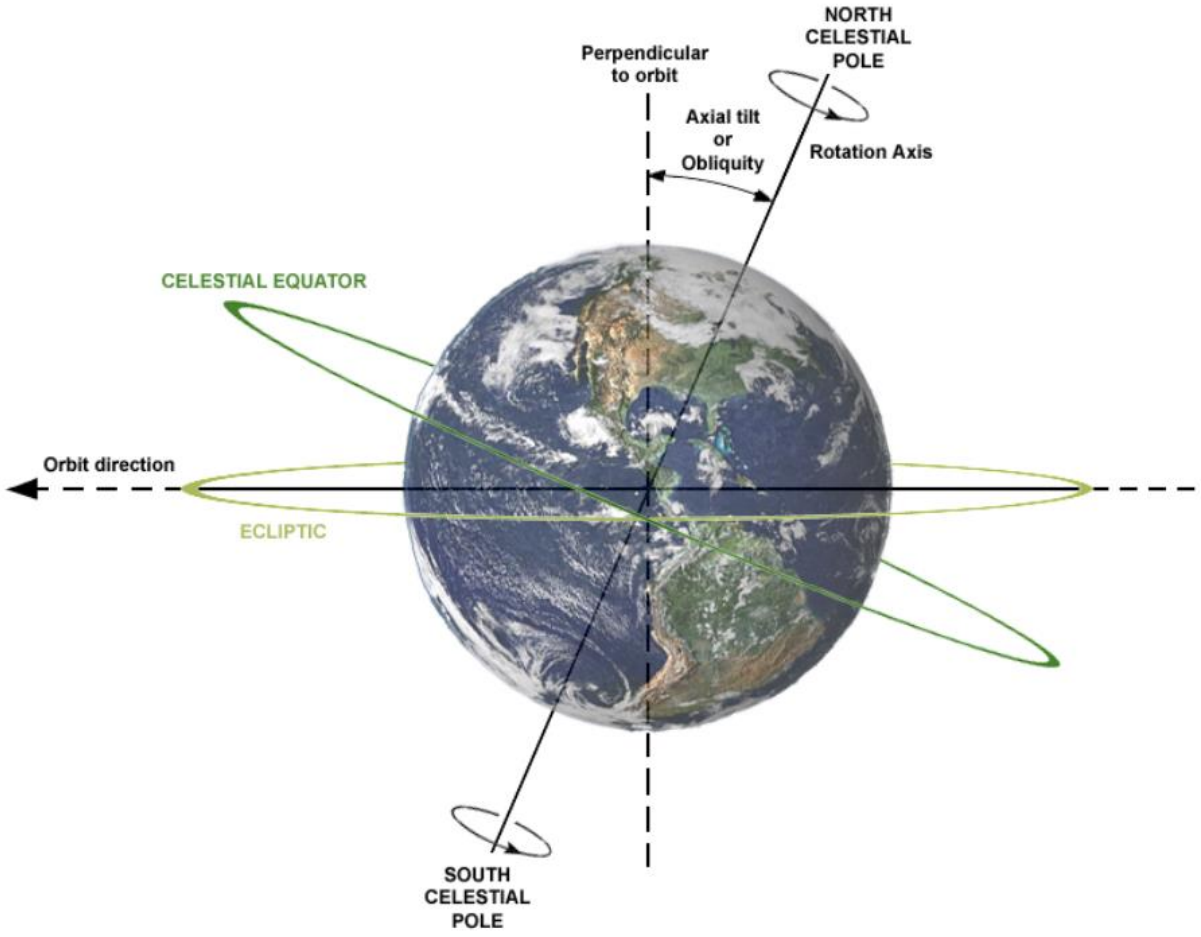

Figure 2 An illustration of Earth's rotation about its polar axis (from earthsci.org)

1.7.1.1 Hypotheses about earth's rotation

- **Cassini's Hypothesis**: Proposed that the Earth rotates about the equator with the polar axis perpendicular to the axis of rotation. This hypothesis should result in a prolate ellipsoid

shape with a side that experiences permanent day light while the other side would be in permanent darkness.

- **Newtonian Hypothesis**: Newton hypothesised that the Earth is rotates about the polar axis which lead to the oblate ellipsoidal shape of the Earth.

The geophysical evidence such as longer equatorial radius than the polar radius, centrifugal sorting of the earth into its density regimes in which the density increases from the surface towards the centre and occurrence of day and night support Newtonian hypothesis.

Other characteristics of the rotating earth:

- The Earth has a circumference (distance around at the Equator) of approximately 40,075 km.
- The Earth rotates on its axis relative to the Sun in one "mean solar day".
- It rotates exactly 360° in one "Mean Sidereal Day" which is 86,164.0909 seconds, or 23 hrs 56 min 4.0909 seconds.
- The distance from one point on the Earth to another point depends on latitude (φ) and is given by: $360 \times 111.41288 \times cos(\varphi) - 0.09350 \times cos(3\varphi) + 0.09350 \times cos(5\varphi)$ in (km).
- The speed at the equator is 1,674 km/hr $(40{,}075 \text{ km} / 23 \text{ hrs } 56 \text{ min } 4.0909 \text{ seconds})$ but at the poles the movement speed is nearly nothing.
- You travel faster than the speed of sound towards the eastern horizon but Earth's rotation is slowing down - about 1 second every 40,000 years.
- The North Star will be Vega instead of Polaris by the year 14,000 AD.

1.7.2 Earth's revolution around the Sun

It takes 365.24 days (one year) for Earth to make one complete revolution around the Sun (Figure 3). Earth and other planets are kept in orbit by the gravitational pull of the Sun. Like the other planets, Earth's orbital path is an ellipse (sometimes closer to the Sun than at other times). The closest Earth gets to the Sun each year is at *perihelion* (147 million km) on about January 3rd and the furthest is at *aphelion* (152 million km) on July 4th. Earth's elliptical orbit has nothing to do with Earth's seasons. During one revolution around the Sun, Earth travels at an average distance of about 150 million km. Earth revolves around the Sun at an average speed of about 27 km/s but the speed is not constant. The planet moves slower when it is at aphelion and faster when it is at perihelion. The reason the Earth (or any planet) has seasons is that Earth is tilted 23½° on its axis. During the Northern Hemisphere summer, the North Pole points toward the Sun, and in the Northern Hemisphere winter the North Pole is tilted away from the Sun.

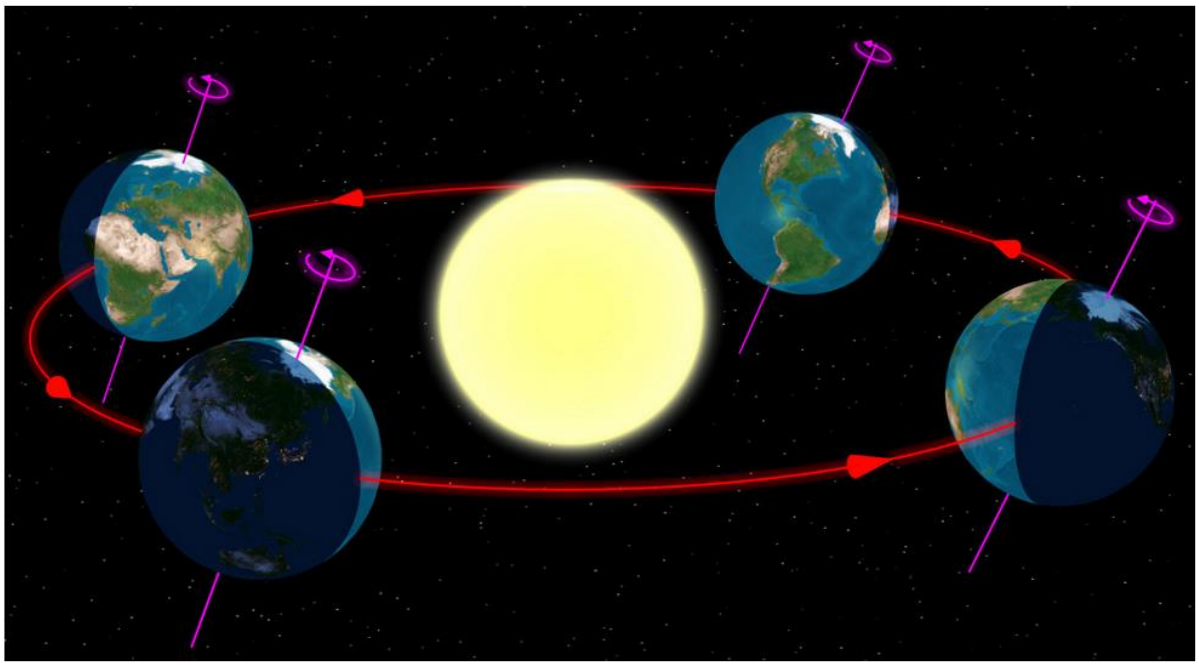

Figure 3 An illustration of Earth's revolution around the Sun (from earthsci.org)

The highlights of Earth's revolution around the sun include:

- The Earth's orbit around the Sun is an ellipse and travels at different speeds during the year - slowest at Aphelion (furthest point from the Sun) and fastest at Perihelion (closest point to the Sun).
- Earth's orbit (the path) is approximately 940,000,000 km in 365.2421896698 days
- So, the "year" is not exactly 365¼ days (sometimes called the Julian Year).
- Earth's speed around the Sun is 107,229 km/hr (939,951,145 km /(365.2421896698 days $*$ 24).

1.7.2.1 Wobbling motion of the Earth

The Earth has been described as an oblate spheroid (not a sphere) with varied geographies contributing to the uneven distribution of mass on the surface. Due to this uneven distribution, Earth wobble as it spins on its axis. The Earth's North-South rotation axis wobbles over a period of 25,770 years. This is known as *Precession* which affects the direction in the sky to which the North Pole points as well as the orientation of the entire orbital path of the Earth. Precession is caused by the gravitational attraction of the Sun (and the Moon) tugging on the Earth's equatorial bulge. Scientists at the National Aeronautics and Space Administration (NASA) have used satellite data on how water moves around Earth to explain the wobbling motion of Earth. According to NASA, the spin axis of the Earth drifted about 10 cm/year in the 20th century.

Three factors responsible for the drift are:

a) contemporary mass loss

b) glacial rebound

c) mantle convection

1.7.2.2 Enormous ice melting

According to some estimates, around 7.5×10^{12} tons of Greenland's ice melted into the ocean as a result of global warming. This is among other sources of mass transfer into the oceans, causing sea level to rise and consequently, a drift in Earth's spin axis. In the year 2000, Earth's spin axis took a sudden turn toward the east and is now drifting almost twice as fast as before, at a rate of almost 17 cm/yr (Adhikari et al., 2018).

1.7.2.3 Glacial rebound

Glacial rebound (assumed to be the primary cause of Earth's wobbling) can be explained as glaciers overburdening the earth with their heavy mass and depressing it. During the last ice age, glaciers depressed earth's surface. And when the ice melted, the land gradually rose to its original place. Based on the statistical analysis of the rebound, NASA scientists have now established that glacial rebound was responsible for about one-third of the drift in the last century. When you fill a sink, the water rises at the same rate to the same height in every corner. That's not the way it works with our rising sea. The sea level is rising a few millimeters a year but this rise is not the same at all shores. The sea level is rising two or three times faster than average on the U.S. East Coast while it's about 25 cm/yr around China's Yellow River delta. Meanwhile it is falling in Scandinavia.

1.7.2.4 Mantle convection

Mantle convection is the circulation of material in the Earth's mantle due to heat radiated from the Earth's core. Mantle Convection is responsible for the movement of tectonic plates beneath the Earth's surface.

Exercise

a) After formation mention 3 processes that warmed up the Earth
b) Name 3 types of motion performed by the Earth
c) According to the hot origin theory, the earth is formed from what remnant particles?
d) Which part of the solid earth is densest?
e) Why is the ocean located on the surface of the earth?
f) What motion is responsible for day and night?
g) What keeps the Earth and other planets in orbit?
h) What is responsible for Earth's seasons?
i) List 3 factors responsible for the drift in earth's spin axis

j) List 5 conditions that make the planet earth a congenial place for living things to survive.

k) Explain the effects, if the distance of the earth from the sun were less or more than what it is now.

l) Justify the formations of ocean and atmosphere above the solid earth.

m) Mention one weakness each of cold and hot origin theories of the earth

2. The Internal and External Structures of the Earth

2.1 Earth's Interior

The internal structure of the Earth consists of 3 major layers— the Crust, Mantle and Core (Figure 4). Our current view of the Earth's formation and subsequent evolution envisions repeated cycles of melt extraction from a convecting fertile mantle, producing mafic magmas that rise to the crust and a complementary residual depleted mantle (Gervilla et. al., 2019). Each episode of crust formation is usually followed by recycling, by which the crust is partially or totally mixed back into the convecting mantle or stored deeper in the Earth.

The Crust: The crust is about 5–56 km on the surface of Earth. Density of rocks is 2,600–3,000 kg/m^3. The thickness of the crust is about 5–11 km in oceans. The crust has been divided into two sub-zones called *Sial* (continental type crust) and *Sima* (oceanic type crust). The Sial is a heterogeneous mixture of rocks while the Sima is a homogenous plastic or semi-plastic concentric layer that behaves like a solid. The Sial floats on the Sima, which in turn floats on the lower concentric layer called the Mantle. Sial contains about 65–75 % silica. Aluminium is the next important element in the Sial, represented by the most common rocks like granite, and rhyolite. Silica decreases to about 50 – 60% in the Sima where aluminium has largely been replaced by magnesium with minor quantities of iron. Sima is represented by the most common rocks like basalt and gabbro at the upper level and by olivine rich rocks at the lower level.

The Mantle: A massive solid to semi solid layer below the crust; 2900 km in thickness; comprises mixed metals and silicate and basic rocks with density of 3,000–4,500 kg/m^3

The Core: Innermost portion of Earth, 3500 km in thickness, contains molten metals like Nickel, iron; average density with density of 9,000–12,000 kg/m^3.

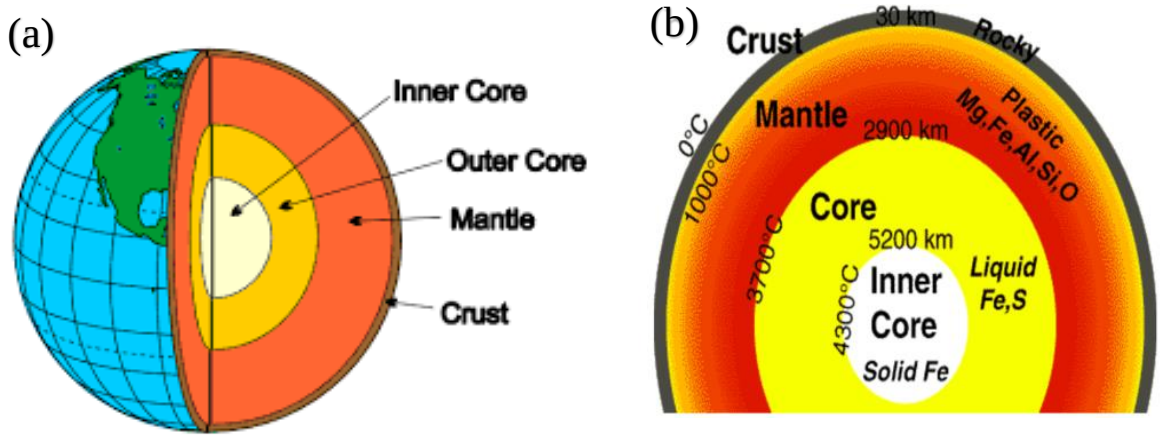

Figure 4 Schematic section through the Earth showing (a) the internal structure, (b) mineralisation and temperature distribution

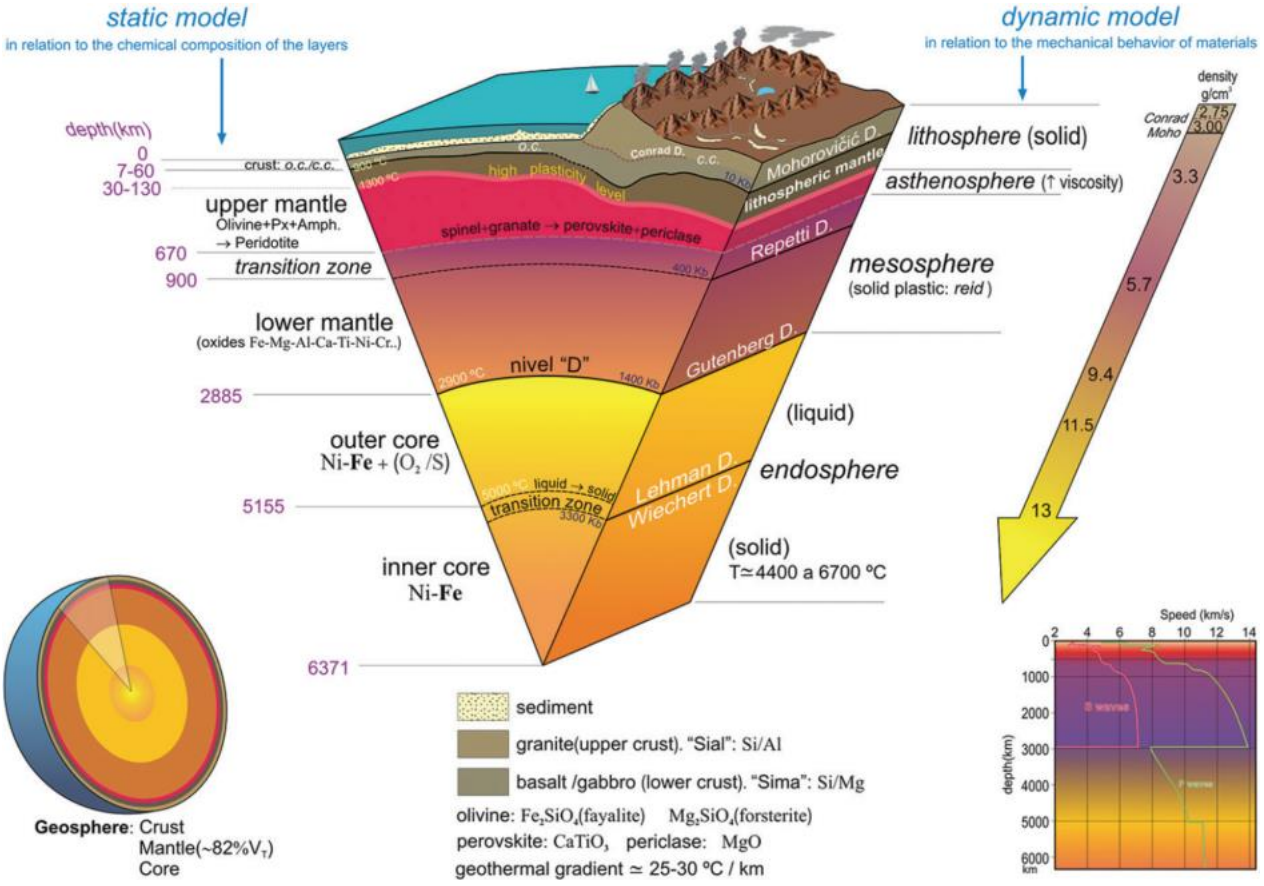

Figure 5 The internal structure of the Earth (Geosphere) is layered in spherical shells, consisting of an outer silicate solid crust, a highly viscous asthenosphere and mantle, a liquid outer core that is much less viscous than the mantle, and a solid inner core. This figure shows this layered structure in terms of chemistry and mineralogy (static model) and mechanical behavior of the constituent rocks (dynamic model). The crust is subdivided into continental (*cc*) and oceanic (*oc*). The picture also includes some physical properties of the different layers, including temperature, pressure, density and speed of P and S seismic waves. (Gervilla et. al., 2019)

2.2 Earth's Exterior

Earth's exterior consists of the lithosphere (solid), the hydrosphere (liquid) and the atmosphere which is gaseous (Figure 6). About 70% of Earth's surface is covered by water (Hydrosphere). The atmosphere is as high as 350 km above the lithosphere/hydrosphere and consists of several layers—the *Troposphere*, *Stratosphere*, *Mesosphere* and *Ionosphere* (Figure 7).

Troposphere – We live in the troposphere, but even near the top of it the air becomes too thin for us to breathe. The top of this layer is called the tropopause and is the level to which clouds and balloons can rise up to.

Stratosphere – The next level up has even thinner air and only a few jet planes can fly in it. Also in this level is the ozone layer, which is an important layer of gas that protects us from a lot of the UV rays from the sun.

Mesosphere – Further up is the mesosphere, or "middle" layer of the atmosphere. The air here gets colder the higher up you go, and is so thin that only rockets can fly through it

Ionosphere – The outer level of the atmosphere is called the ionosphere, which is made up of the thermosphere and the far-out exosphere. Here the air is so thin that it can barely be called air! This is the level where we see the auroras (Northern and Southern Lights) and where we can first see meteors when bits of rock enter the atmosphere from outer space and begin to burn up.

Pressure decreases with height above the lithosphere which causes air molecules to spread farther apart to create *thin air*. The air gets extremely thin at very high atmospheric heights.

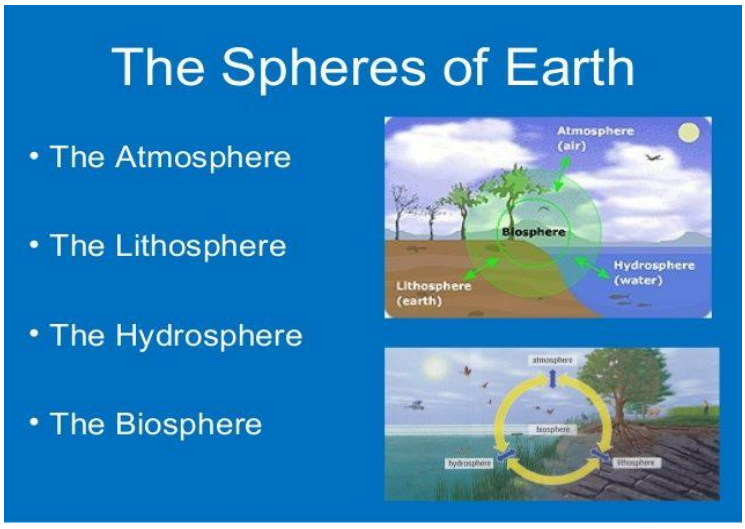

Figure 6 The Spheres of Earth

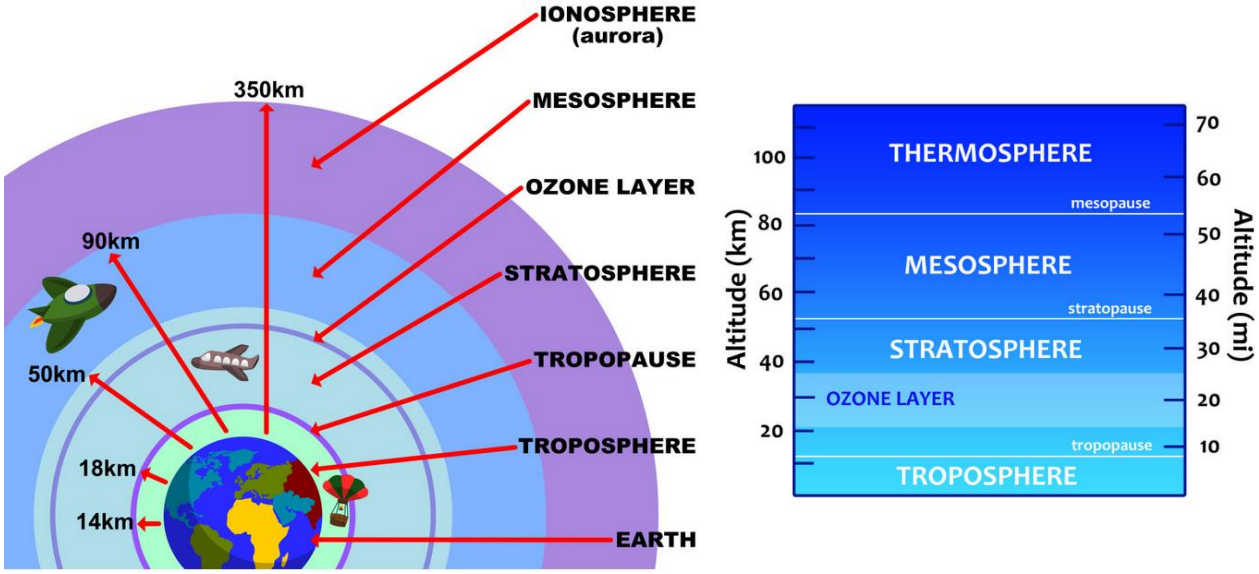

Figure 7 A schematic diagram of earth showing the layers of the atmosphere

Exercise

a) Name two sub-divisions of the crust and their main mineral content

b) The atmosphere consists of several layers. Name 3 of the layers.

3. Earth's Shape and Gravity Field

The science of measuring and understanding Earth's geometric shape, orientation in space and gravitational field is called *Geodesy*. In geodesy the Earth is approximated to an oblate *ellipsoid* (closed surface of which all plane cross-sections are either ellipses or circles) that best fit a *geoid* (a hypothetical solid Earth model of global mean sea level from which topographic heights and ocean depths are measured). So, the mathematical approximation of the geoid is the *oblate ellipsoid* or *spheroid of revolution* (Figure 8).

Earth's gravity is the net acceleration that is imparted to bodies as a result of the combined effect of gravitation (from mass distribution within Earth) and from the Earth's rotation (the centrifugal force). The normal gravitational acceleration g_N (Figure 8) of the Earth is determined based on an oblate ellipsoid that best approximates the geoid. The geoid is also described as the gravitational equipotential surface that best approximate the shape of the Earth. That is, the summation of the potential of the gravitational attraction and centrifugal force of the Earth's rotation is constant on this surface which most closely corresponds to the ocean's surface. The gravitational accelerations due to these forces are not constant on this surface because the force is a function of the spatial rate of change of potential.

The surface of the Earth is not an inertia frame of reference because of the Earth's rotation which produces a larger centrifugal force near the Equator than in areas near or at the poles. Consequently, objects experience a weaker gravitational field around the Equator (by a maximum of 0.3%) than at the geographic poles (or polar regions). The centrifugal force imparts an acceleration to a body that is equal to the product of the square of the angular velocity of the Earth and the perpendicular distance between the axis of rotation and the body (the *radius of gyration*). This acceleration is vectorially added to the gravitational acceleration of the Earth. The centrifugal acceleration and the radius of gyration are both maximum at the Equator but directly opposite each other. However, the effect of centrifugal acceleration and the radius of gyration are both zero at the poles. The theoretical gravity that accounts for the mass, shape, and rotation of the Earth is based on an assumed terrestrial ellipsoidal surface determined by the International Union of Geodesy and Geophysics to be called the *Geodetic Reference System*. The reference ellipsoid deviate from the geoid by a maximum of ±100 m which is negligible compared with the radius of the Earth.

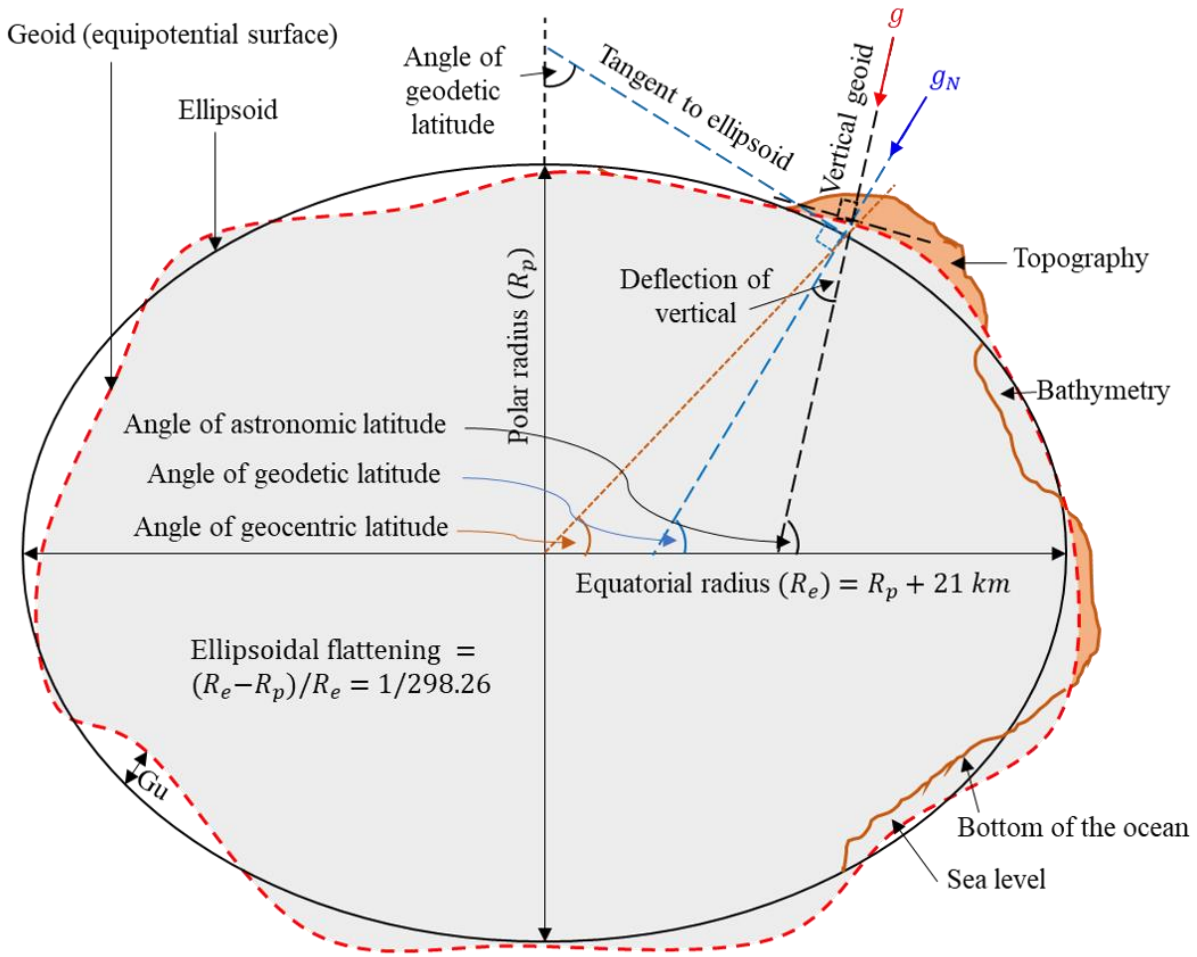

Figure 8 An illustrative diagram showing the geoid (dashed red line), the ellipsoid and the basic geodetic parameters

3.1 Spatial and Temporal Variations of Earth's Gravity Field

The Earth's gravity field varies both spatially and temporally to distort the changes in the anomaly fields caused by local subsurface conditions of interest in gravity surveys. The *spatial variations* are due to the shape, size and rotation of the Earth while the *temporal variations* are due to terrestrial bodies (like the Moon and Sun). These effects are large compared with many geological gravity effects and must be removed from gravity measurements before processing. The *tidal effect* of the Moon and Sun on gravity measurements, although small (about 0.33 mGal over a day period) are usually removed before representing a picture of global gravity (Figure 9)

Furthermore, the Earth's equatorial bulge causes objects at the Equator to be farther from the planet's centre than objects at the poles. The equatorial bulge combined with the effects of surface centrifugal force due to rotation result in an increase in sea-level gravity from about 978.0 Gal at the

Equator to about 983.2 Gal at the poles (about 0.5% increase in the weight of objects). Gravity on the Earth's surface varies by some 0.7%, between 976.39 Gal on the Nevado Huascarán mountain in Peru to 983.37 Gal at the surface of the Arctic Ocean (Hirt et al., 2013). In large cities, it ranges from 977.60 Gal in Kuala Lumpur, Mexico City, and Singapore to 982.5 Gal in Oslo and Helsinki (https://en.wikipedia.org/wiki/Gravity_of_Earth).

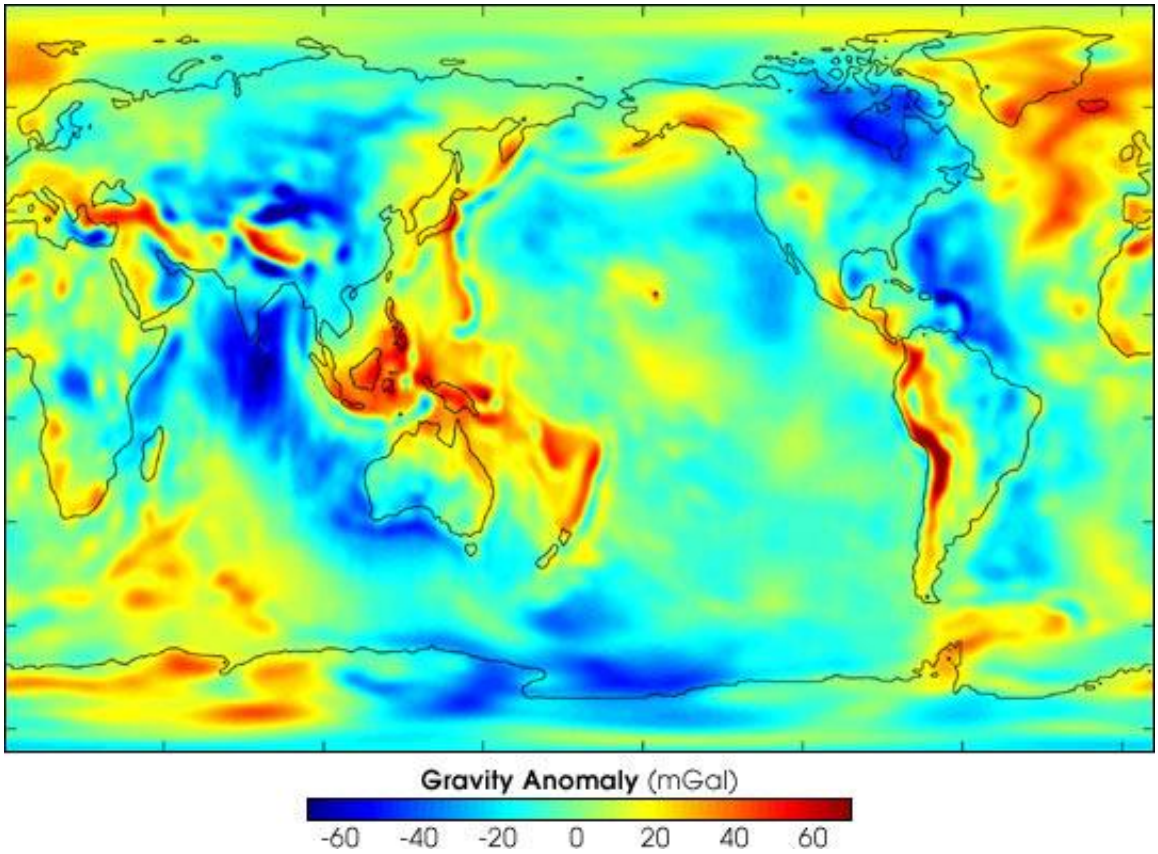

Figure 9 Earth's gravity field variations (image from earthobservatory.nasa.gov)

3.2 Rock Densities

The density of rocks in the Earth varies widely (see Table 3 and Figure 10). The SI unit of density is megagram per cubic metre (Mg/m^3) which is numerically equivalent to grams per cubic centimetre (g/cm^3). Based on formation, rocks are classified into three groups: *sedimentary*, *metamorphic*, and *igneous* (in increasing order of density). Sedimentary rocks are the least dense among the three rock types. Factors that affect the density of sedimentary rocks include *mineral composition*, *porosity*, *pore–fluid type*, *cementation*, *age of rock, depth of burial*, and *tectonic processes*. Also, buried sediments *consolidate* (*formed by compaction, deposition of cement in pore*

spaces, or by physical and chemical changes in the original sediments) and *lithify* (*change into solid rock)* over time which result to less *porosity* and increased density. Under normal circumstances, the density contrast between adjacent sedimentary strata is barely above 0.25 g/cm^3. Metamorphic rocks are derived from both igneous and sedimentary rocks that have been altered deep in the crust by increased lithostatic pressure, tectonic stress, and enhanced temperatures. Metamorphic rocks have the most varied density range which increase with decreasing acidity and with increasing grade of metamorphism. Igneous rocks originate from magma that has solidified within the Earth (plutonic) and at the surface (volcanic). They are generally denser than sedimentary and metamorphic rocks, but their density decreases with increasing silica content. Acidic igneous rocks tend to be less dense compared to the basic ones while volcanic rocks are usually less dense than plutonic rocks.

Unconsolidated sediments are made up of the fragments derived from erosion of preexisting rocks that are commonly deposited in water or less commonly in air and by chemical precipitants. Sedimentary rocks consist of sediments that have been lithified by lithostatic pressure and chemical precipitants. The component minerals and the origin and nature of the void space in these three classes generally occur within specified ranges, facilitating consideration of their densities.

Table 3 Densities of common rocks and minerals (after Alden 2019, https://structx.com)

Rock Type	**Bulk density**		**Porosity**	**Elastic Modulus**		**Poisson's**
	(Mg/m^3)	(lb/ft^3)	(%)	(GPa)	(ksi)	**Ratio**
Igneous	2.21–3.00	138–187	0.10 – 22.1	10–100	1540–14504	0.10–0.40
Granite	2.53–2.62	158–164	1.02 – 2.87	30–70	4351–10153	0.17
Diorite	2.80–3.00	175–187	0.10 – 0.50	30–100	4351–14504	0.10–0.20
Gabbro	2.72–3.00	170–187	1.00 – 3.57	40–100	5802–14504	0.20–0.35
Rhyolite	2.40–2.60	150–162	0.40 – 4.00	10–50	1450–7252	0.20–0.40
Andesite	2.50–2.80	156–175	0.20 – 8.00	10–70	1450–10153	0.20
Basalt	2.21–2.77	138–173	0.22 – 22.1	40–80	5802–11603	0.10–0.20
Sedimentary	1.82–2.76	114–172	–	5–90	725–13053	0.10–0.30
Conglomerate	2.47–2.76	154–172	–	10–90	1450–13053	0.10–0.15
Sandstone	1.91–2.58	119–161	1.62 – 26.4	15–50	2176–5272	0.14
Shale	2.00–2.40	125–150	20.0 – 50.0	5–30	725–4351	0.10
Mudstone	1.82–2.72	114–170	–	5–70	725–10153	0.15
Dolomite	2.20–2.70	137–169	0.20 – 4.00	30–70	4351–10153	0.15
Limestone	2.67–2.72	167–170	0.27 – 4.10	20–70	2901–10153	0.30
Metamorphic	2.18–3.30	136–206	–	5–90	725–13053	0.15–0.30
Gneiss	2.61–3.12	163–195	0.32 – 1.16	30–80	4351–11603	0.24
Schist	2.60–2.85	162–178	10.0 – 30.0	5–60	725–8702	0.15–0.25
Phyllite	2.18–3.30	136–206	–	10–85	1450–12328	0.26
Slate	2.71–2.78	169–174	1.84 – 3.64	20–90	2901–13053	0.20–0.30
Marble	2.51–2.86	157–179	0.65 – 0.81	30–70	4351–10153	0.15–0.30
Quartzite	2.61–2.67	163–167	0.40 – 5.9	50–90	7252–13053	0.17

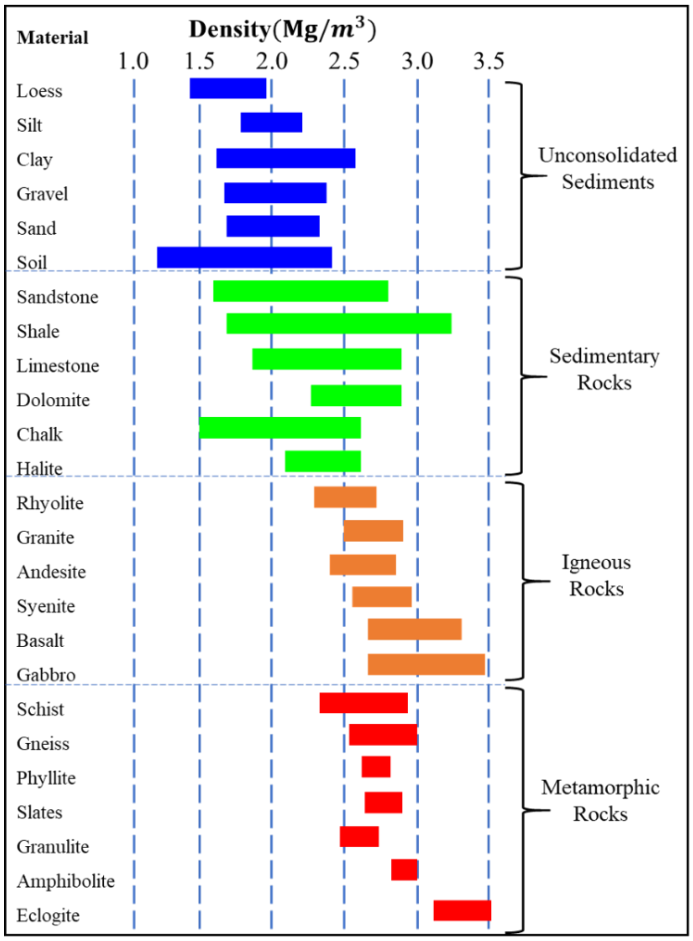

Figure 10 Variations in density for different rock types (after Telford et al., 1990)

Exercise

a) What is the geoid?

b) What is responsible for the temporal variation of Earth's gravity?

c) Based on formation, what are the three types of rocks?

d) List 3 factors that affect the density of sedimentary rocks

4. The Earth's Magnetic Field

The geomagnetic field at or near the surface of the Earth arises largely from within and around the Earth's core (see Figure 11).

The Earth's magnetic field can be divided into three components:

a) the main field which originates from the Earth's interior and varies very slowly;
b) a field originating from outside of the Earth but small when compared to the main field and varies more rapidly;
c) spatial variations (mainly invariant in the time and place) of the main field due to inhomogeneities of the Earth's crust.

Additionally, the flow of conducting sea water through the ambient magnetic field induce electric currents that also contribute to the observed magnetic field (Chulliat et al., 2020).

The geomagnetic field is approximated to the field of a magnetic dipole, tilted at an angle of about 11.5º (degrees) with respect to Earth's rotational axis. The geomagnetic field has an average value of about 50,000 nT and changes slowly over time– a phenomenon called secular variation of the magnetic field. In the 1980s, the North and South geomagnetic poles intersect the Earth's surface roughly at 72.5º N, 70º W and 78.5º S, 100º E. Based on the 2020 World Magnetic Model (WMM2020), the location of the poles in 2020 have changed significantly to 80.59º N, 72.68º W and 80.37º S, 107.32º E (Table 4). The polarity of the Earth's field is believed to reverse over geological time scales leaving evidence in rocks.

Table 4 Computed pole positions based on the WMM2020

Geomagnetic Poles	2020.0	72.68° W 80.59° N (geocentric) 80.37° S (geodetic)	107.32° E 80.59° S (geocentric) 80.37° S (geodetic)
Model Dip Poles	2020.0	164.04° E 86.50° N (geodetic)	135.88° E 64.07° S (geodetic)

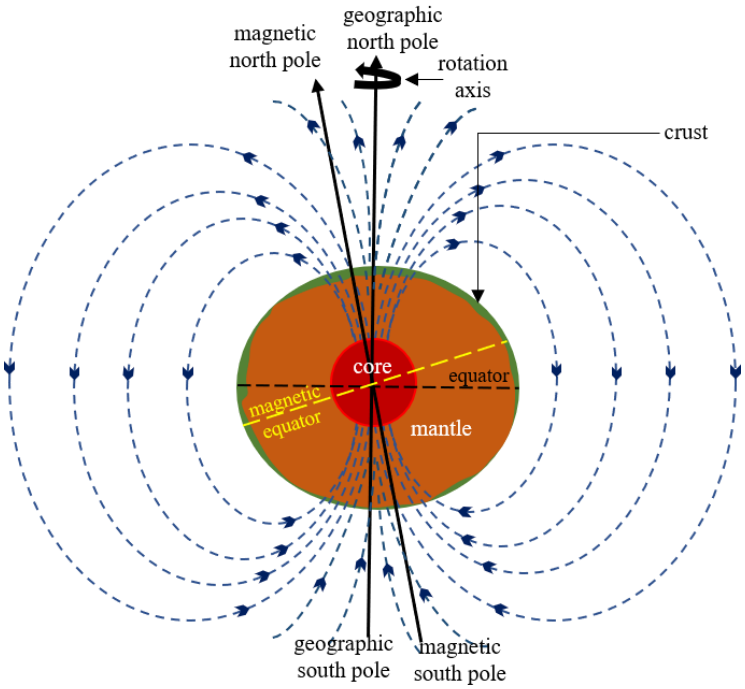

Figure 11 Schematic section through the Earth showing the structure and the main magnetic field

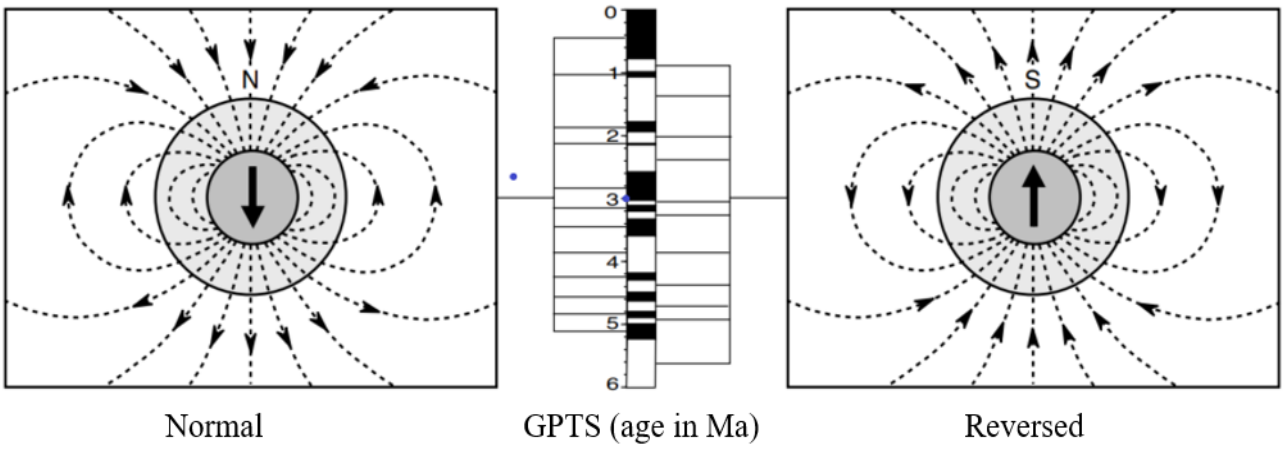

Figure 12 Schematic representation of the geomagnetic field of a geocentric axial dipole (Langereis et al., 2010)

Exercise

a) List the three components of Earth's magnetic field

b) What is secular variation of the geomagnetic field?

5. Origin of Earth's Magnetic Field

That the Earth's magnetic field is generated by electric currents due to convection of molten iron in the outer core of the earth was suggested in the late 1940s in the work of W. Elasser and E. Bullard (Campbell, 2003). This is based on the electromagnetic theory which suggests that moving charges cause a magnetic field. However, the process may be more complex and has not been fully understood.

Paleomagnetism is the study of magnetic imprint in rocks over geological time scales. Paleomagnetic evidence indicates that the magnetic field is usually oriented almost parallel to Earth's axis of rotation (Figure 11) which supports the electromagnetic theory, suggesting that convection of molten iron in the outer core is connected to the Earth's spin. Observation of the Earth's magnetic field shows that, as lava cools into solid rock, tiny crystals of a magnetic mineral called magnetite can record the *strength* and *direction* of the Earth's magnetic field at the time of the rock's formation. Using relatively simple trigonometric equations, geologists can take this data and determine the latitude at which a certain rock formed. This procedure was applied to igneous rocks from across the globe, and it was discovered that the latitudes at which the rocks formed were different than the latitudes they occupy today. The positions of the North and South magnetic poles are relatively stable but reverses polarity (pole reversals) at irregular intervals (Figure 12) over geomagnetic polarity time scale (GPTS). Evidence of multiple nonperiodic pole reversals is in the stratigraphic record of magnetic zonation of sedimentary sequences studied in magnetostratigraphic dating. Based on the 2020 World Magnetic Model (WMM2020), the total magnetic field intensity variation is shown in Figure 13.

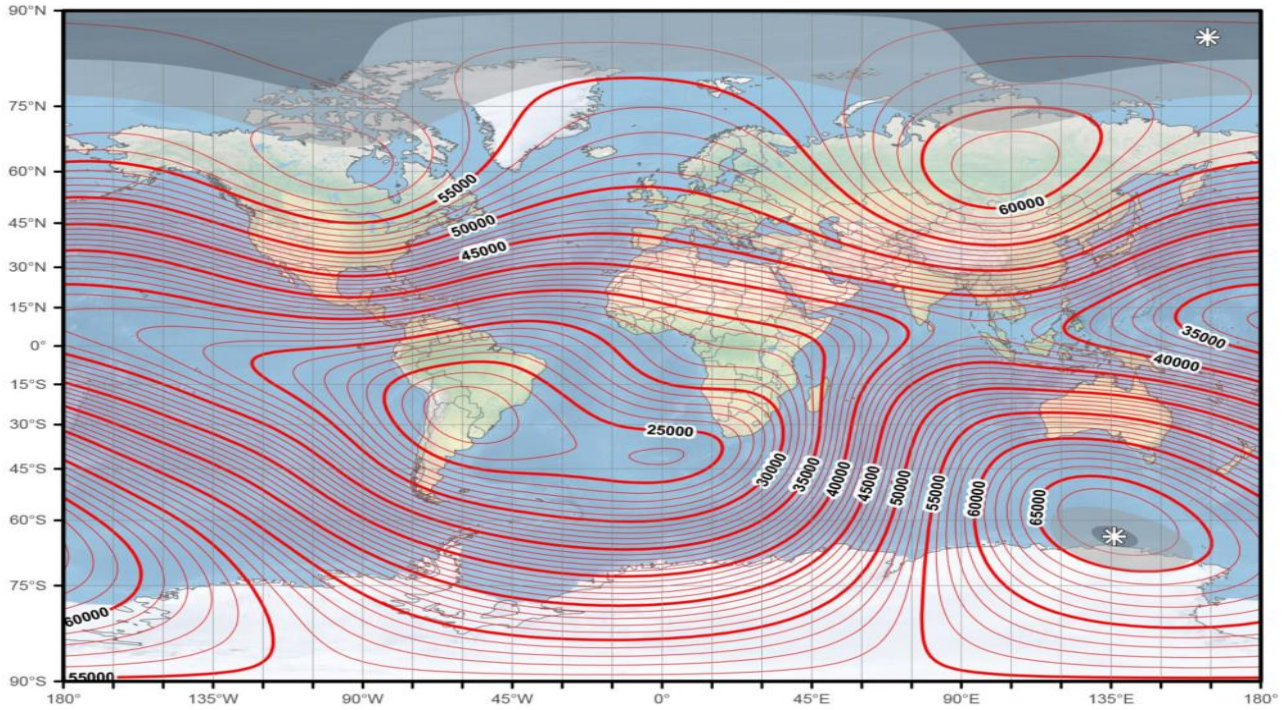

Figure 13 Main magnetic field total intensity. Miller projection. (WMM2020)

5.1 The External Magnetic Field

The changes in geomagnetic field caused by external sources have lower amplitude than changes stemming from the internal changes, however, their period is much shorter and thus could seriously affect magnetic survey. The periodical variations are the *Solar diurnal variations* (with amplitude of several tens of nT and a period of 24 hours associated with the rotation of the earth) and *Lunar diurnal variations* with a period of 25 hours and amplitude of a few nT. *Micropulsations* are short period variations with periods of tenth of seconds up to tens of minutes with amplitudes from a tenth of nT up to tens of nT. The shape of a recorded sequence of micropulsations can change with location over a few tens of kilometers **(**Reeves, 2005**)**. Periodic or random magnetic variation believed to be caused by solar activities (e.g., *magnetic storms*) could appear several times per month and last for several days. The amplitude of the storms could be several thousands of nT and have a random fluctuation. Effects of these variations could be easily removed from the measured magnetic data in a similar way as in the gravity prospection – using a base station and subtracting the base-station data from the measured ones. However, the magnetic storm could be random with high amplitudes and would be best to avoid measurements during a storm. The sources of magnetic anomalies could not be very deep since temperatures below ~ 40 km should rise above the curie point temperature (≈ 550 ◦C) at

which rocks lost their magnetic properties. Thus, local anomalies must be associated with features in the upper crust.

5.2 Spatial Variations of the Main Field

The spatial variation of Earth' main magnetic field originate from the local change in concentration of magnetic minerals in the near surface rocks. Magnetic anomalies are deviations from the average magnetic field of an area. Magnetic anomalies recorded during surveys are caused by the interaction of the geomagnetic field with the rocks of the Earth's crust. Magnetic materials (e.g., magnetite, titanmagnetite, titanhematite, maghemite and pyrrhotite) can cause magnetic anomalies either due to high remanent magnetization or due to large magnetic susceptibilities. However, anomalies recorded during magnetic surveys are predominantly due to the presence of naturally occurring magnetite— an oxide of iron with the chemical formula Fe_3O_4.

5.3 Magnetism in Rocks

Rocks can become magnetized when placed in an external magnetic field. The magnetic properties of these rocks are either due to induction by the external magnetic field or due to natural remanent magnetisation (NRM) by the presence of an earlier external inducing field. The most common types of NRM are thermoremanent magnetization, detrital magnetization, chemical remanent magnetization, isothermal remanent magnetization, viscous remanent magnetization and dynamic remanent magnetization (Valenta, 2015). The degree of magnetization in the presence of Earth's magnetic field is partly determined by the magnetic susceptibility of the rock.

The magnetic behaviour of rocks are determined by many factors which include:

(i) the intensity and orientation of the inducing magnetic field;
(ii) the bulk chemistry of the rocks;
(iii) the type of magnetization (induced, remanent etc.) of the magnetic mineral species;
(iv) the percentage of iron and titanium (the primary opaque oxide minerals in all rocks);
(v) the silicates of iron and magnesium.

Exercise

a) List the three components of Earth's magnetic field
b) What is secular variation of the geomagnetic field?
c) List 3 factors that can affect the magnetic behaviour of rocks.
d) What is responsible for the spatial variation of earth's main magnetic field?

6. Seafloor Spreading, Continental Drift and Plate Tectonics

6.1 Seafloor Spreading

Seafloor spreading is a process that occurs at mid-ocean ridges, where new oceanic crust is formed through volcanic activity and then gradually moves away from the ridge. For example, Cambridge geologists Drummond Matthews and Fred Vine measured the magnetic fields in the rocks of the ocean floor and found that the strength and direction of the fields followed striped patterns that were the same on both sides of the ridges. Later studies directly dated the rock of the seafloor and found that the absolute dates were also symmetrical around the ridges, with rocks becoming older with distance from the hypothesized spreading center. An influx of additional data only confirmed that new seafloor was created in mid-ocean ridges and gradually spread outward in both directions.

Seafloor spreading gave credence to the concept of continental drift in the theory of plate tectonics.

- When oceanic plates diverge, tensional stress causes fractures to occur in the lithosphere.
- The motivating force for seafloor spreading ridges is tectonic plate slab pull at subduction zones, rather than magma pressure, although there is typically significant magma activity at spreading ridges.
- Plates that are not subducting are driven by gravity sliding off the elevated mid-ocean ridges by a process called *ridge push*.
- At a spreading center, basaltic magma rises up the fractures and cools on the ocean floor to form new seabed. Hydrothermal vents are common at spreading centers.
- Older rocks will be found farther away from the spreading zone while younger rocks will be found nearer to the spreading zone.

Outcrops and borehole samples from across the globe are continually assembled into a *magnetostratigraphical chart* which can be useful for estimating seafloor *spreading rate* (Figure 14 and 15). Spreading rate is the rate at which an ocean basin widens due to seafloor spreading. The rate at which new oceanic lithosphere is added to each tectonic plate on either side of a mid-ocean ridge is the *spreading half-rate* (equals half of spreading rate). Spreading rates can be classified as: fast (more than 9 cm/yr), intermediate (4–9 cm/yr), and slow (less than 4 cm/yr) (Macdonald, 1982; Searle, 2013). The highest known rate was over 20 cm/yr during the Miocene on the East Pacific Rise (Wilson, 1996).

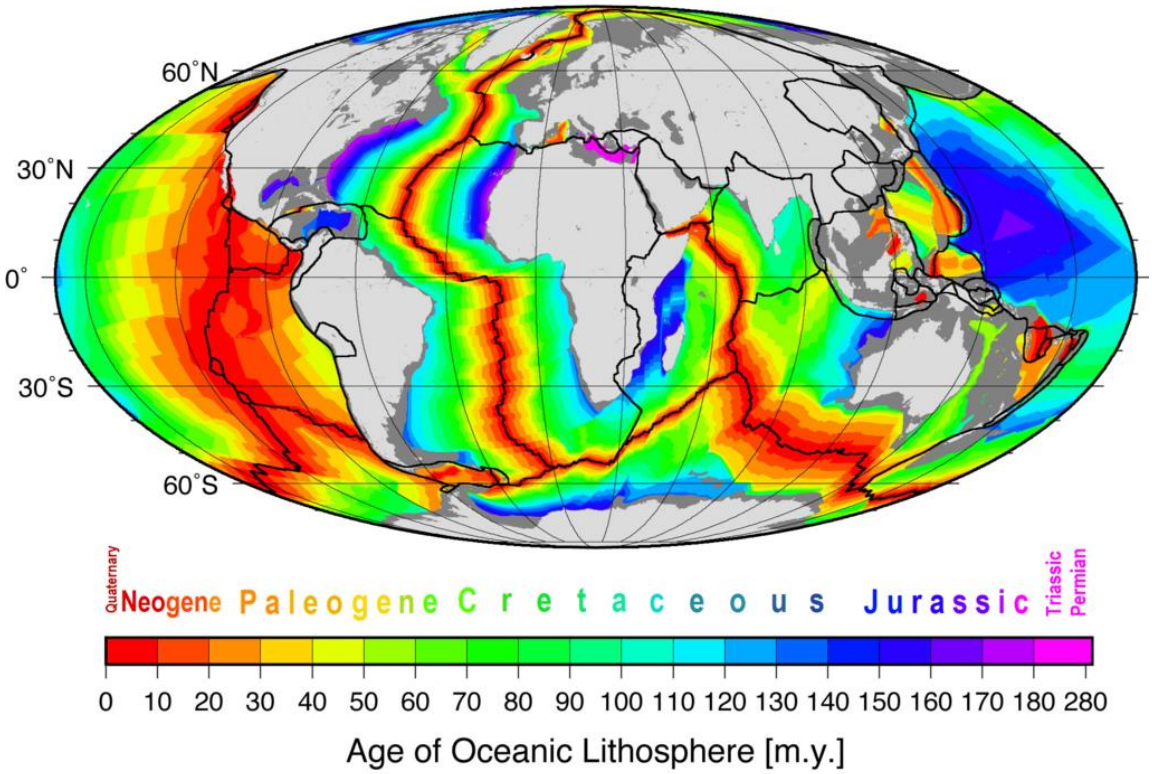

Figure 14 Age of oceanic lithosphere; youngest (red) is along spreading centers (figure from http://www.ngdc.noaa.gov/mgg/ocean_age/ocean_age_2008.html)

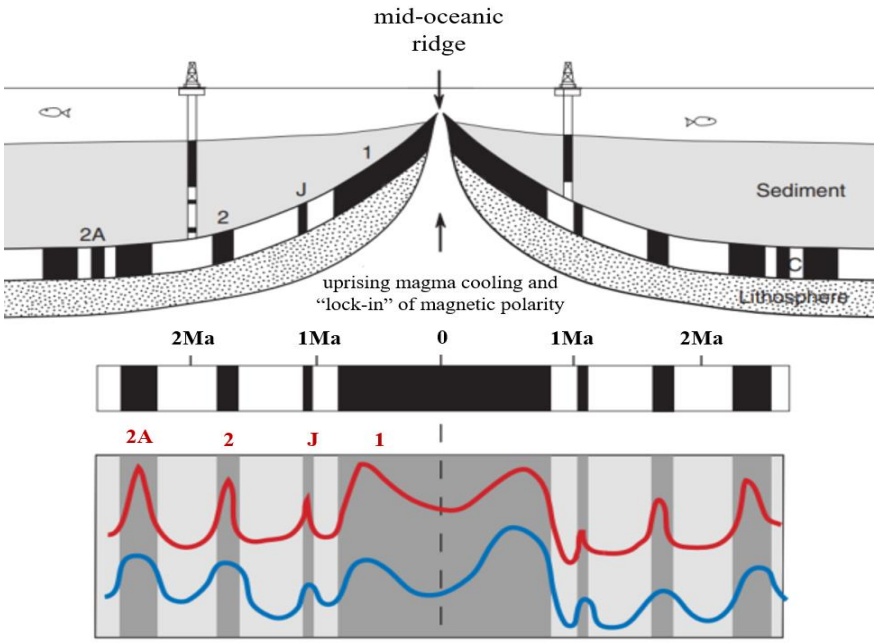

Figure 15 Formation of marine magnetic anomalies during seafloor spreading (after Langereis et al., 2010)

6.2 Continental Drift

Continental drift (Figure 16) is the hypothesis that the Earth's continents have moved over geologic time relative to each other, thus appearing to have "drifted" across the ocean bed. It was proposed by Alfred Wegener in 1912. Although long before Wegener's proposal, philosophers and geographers had recognized that the coasts of Africa and South American snugly fits together like a jigsaw puzzle. Earlier in 1596 Abraham Ortelius (a geographer) suggested that the Americas were once conjoined with Europe and Asia.

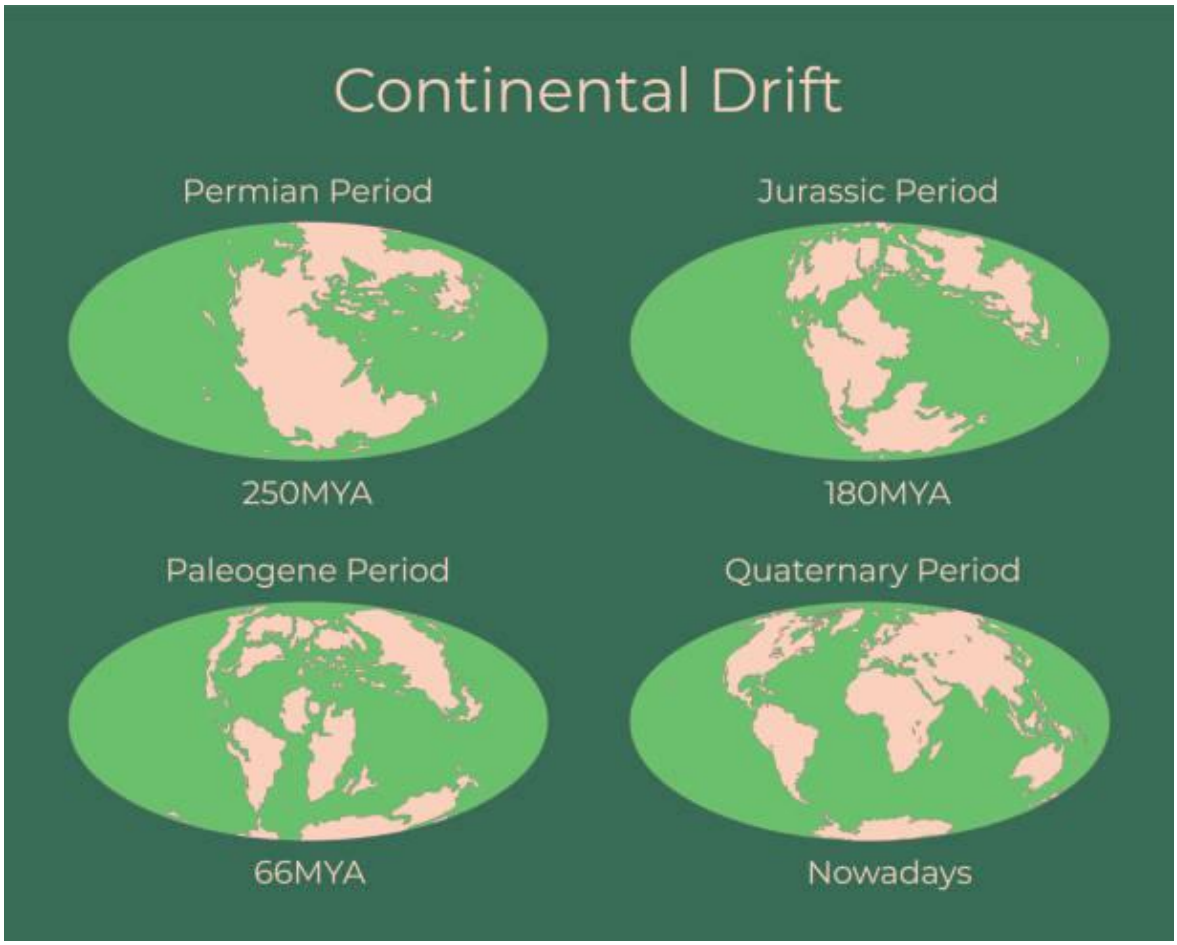

Figure 16 Continental drift and changes of Earth map (Image credit: https://www.istockphoto.com)

- The hypothesis was able to explain the existence of look-alike plant and animal fossils, and similar rock formations that are found on different continents.
- Not only did the coastlines of South America and Africa match, but so too did the coasts of Newfoundland, England, parts of Greenland, and Scandinavia.
- The Paleozoic fossils shared by South America and Africa were only the tip of a paleontological iceberg of supporting observations. As it turned out, South America, Africa,

Australia, Antarctica, and India shared a mélange of Paleozoic and Mesozoic fossils, including a unique tropical plant flora characterized by the fern *Glossopteris* and a reptile fauna that included the tusked, pig-like *Lystrosaurus*.

Other evidence revealed by Wegener included:

- closely matching rock units shared by Africa and South America
- the distributions of former equatorial climate belts (as shown by coals and fossil reefs shared by the five forementioned lands)
- the locations of past Paleozoic glaciations.

Taken together, these facts suggested to Wegener that all the continents had once been joined together into a supercontinent named *Pangaea*, which later split into two large fragments. The first included North America, Europe, and Asia, while the second consisted of Africa, South America, India, Madagascar, Australia, and Antarctica, all of which separated later.

But the theory was unsuccessful in providing the mechanism for the movement of continents. Wegener suggested that the centrifugal force resulting from the Earth's rotation, or possibly the pull of gravity from the moon, drove the lighter, granite-rich continents through the denser, basalt-rich oceanic crust like a ship plowing through water. However, eminent Cambridge geologist Harold Jeffreys, one of the most respected scientists of his time, did the calculations and found these forces insufficient to move something as large as a continent. As a result, the theory was discarded at that time.

Scientists later confirmed the movement of plates and some of Wegener's ideas, such as the past existence of a supercontinent (Pangaea) joining all the world's landmasses as one. Over the course of the 1960s, a handful of young earth scientists from across the globe would mold new scientific observations into the theory of plate tectonics, which today explains everything from animal dispersal and mountain building to volcanism and earthquakes. Pangaea was a supercontinent that formed roughly 200 to 250 million years ago, according to the U.S. Geological Survey (USGS) and was responsible for the fossil and rock clues that led Wegener to his theory (Figure 17).

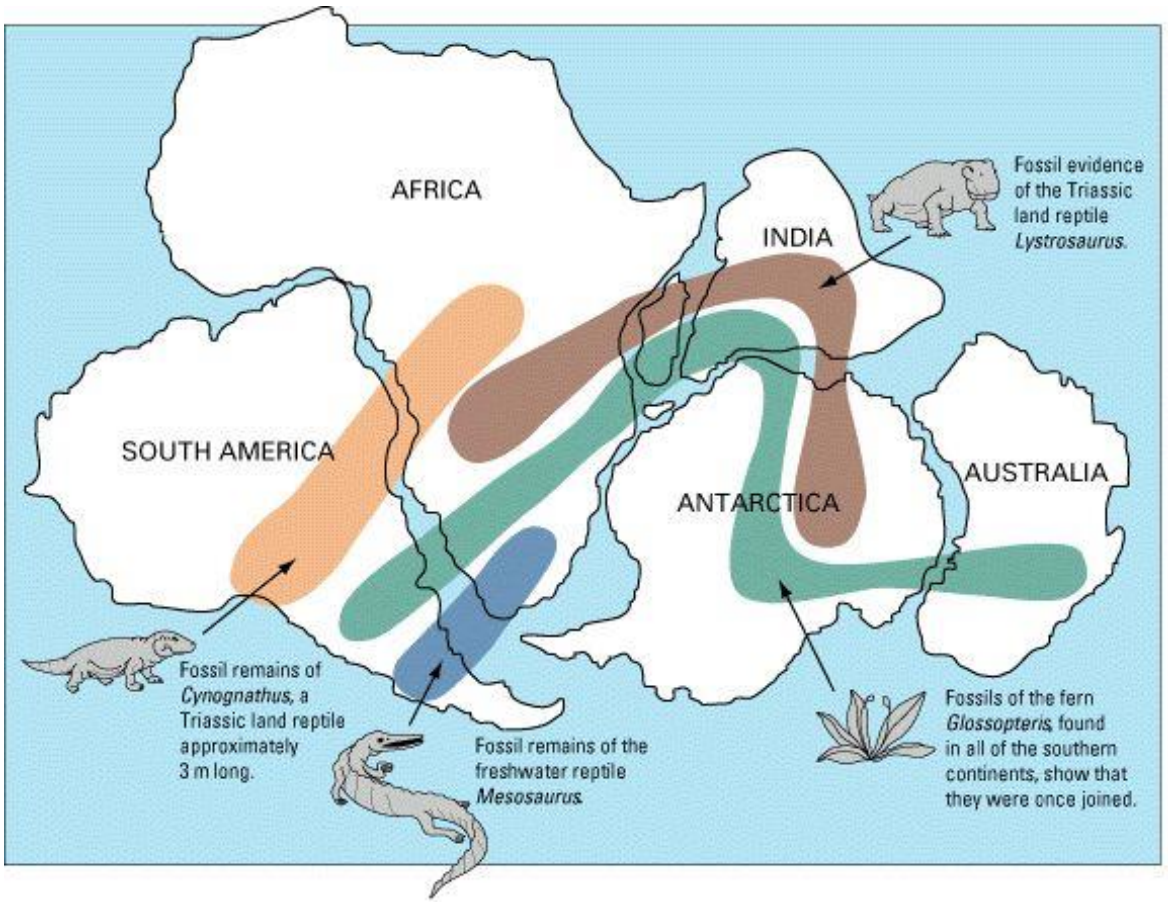

Figure 17 The theory of continental drift reconciled similar fossil plants and animals now found on widely separated continents. Gondwana is shown here. (Image credit: USGS)

6.3 Plate Tectonics

Plate tectonics is the theory that explains the function of the uppermost layers of the planet. The top surface of the earth, the crust and upper mantle, is separated into 7 major tectonic plates (*African, Antarctic, Eurasian, North American, South American, Pacific,* and *Indo-Australian*) and many other small ones (e.g., *Arabian, Caribbean, Juan de Fuca, Cocos, Nazca, Philippine Sea,* and *Scotia*). The Indo-Australian plates is sometimes subdivided into the *Indian* and *Australian* plates. These plates (15–200 km thick) are moving relative to each other at different speeds.

6.3.1 Key principles of plate tectonics

- The lithosphere (crust and upper mantle) is broken into tectonic plates.
- The lithosphere exists as separate and distinct tectonic plates floating on the asthenosphere which is a *visco-elastic* solid (property of materials that exhibit both viscous and elastic characteristics when undergoing deformation). This division is based on differences in mechanical properties

and in the method for the transfer of heat. The lithosphere is cooler and more rigid, while the asthenosphere is hotter and flows more easily. (This division should not be confused with the chemical subdivision of these same layers into the *mantle* (comprising both the asthenosphere and the mantle portion of the lithosphere) and the crust: a given piece of mantle may be part of the lithosphere or the asthenosphere at different times depending on its temperature and pressure)

- In terms of heat transfer, the lithosphere loses heat by conduction, whereas the asthenosphere also transfers heat by convection and has a nearly adiabatic temperature gradient.
- Most of the continents are on single plates, called continental plates, and the plates under the ocean are called oceanic plates.
- The rocks under the ocean are usually heavier types than the rocks on land, plus the weight of the ocean also counts, so most oceanic plates are thin while continental plates can be up to 200 km thick.
- Plate motions range up to a typical 1–4 cm/yr (Mid-Atlantic Ridge; about as fast as fingernails grow), to about 16 cm/yr (Nazca Plate; about as fast as hair grows) (Hancock, 2000).

The thickness of oceanic lithosphere ranges between 6–100 km from creation and destruction. They are created at mid-ocean ridges and spreads outwards. Continental lithosphere is typically about 200 km thick, though this varies considerably between basins, mountain ranges, and stable cratonic interiors of continents.

The location where two plates meet is called a plate boundary. Plate boundaries are commonly associated with geological events such as earthquakes and the creation of topographic features such as mountains, volcanoes, mid-ocean ridges, and oceanic trenches. The majority of the world's active volcanoes occur along plate boundaries, with the Pacific Plate's Ring of Fire being the most active and widely known today. Some volcanoes occur in the interiors of plates, and these have been variously attributed to internal plate deformation and to mantle plumes.

6.3.1.1 Oceanic plates versus continental plates

The distinction between oceanic crust and continental crust is based on their modes of formation:

- Oceanic crust is formed at sea-floor spreading centers while continental crust is formed through arc volcanism and accretion of terranes through tectonic processes, though some of these terranes may contain ophiolite sequences, which are pieces of oceanic crust considered to be part of the continent when they exit the standard cycle of formation and spreading centers and subduction beneath continents.

- Oceanic crust is also denser than continental crust owing to their different compositions. Oceanic crust is denser because it has less silicon and more heavier elements ("mafic") than continental crust ("felsic") As a result of this density stratification, oceanic crust generally lies below sea level (e.g. most of the Pacific Plate), while continental crust buoyantly projects above sea level. https://en.wikipedia.org/wiki/Plate_tectonics#Key_principles

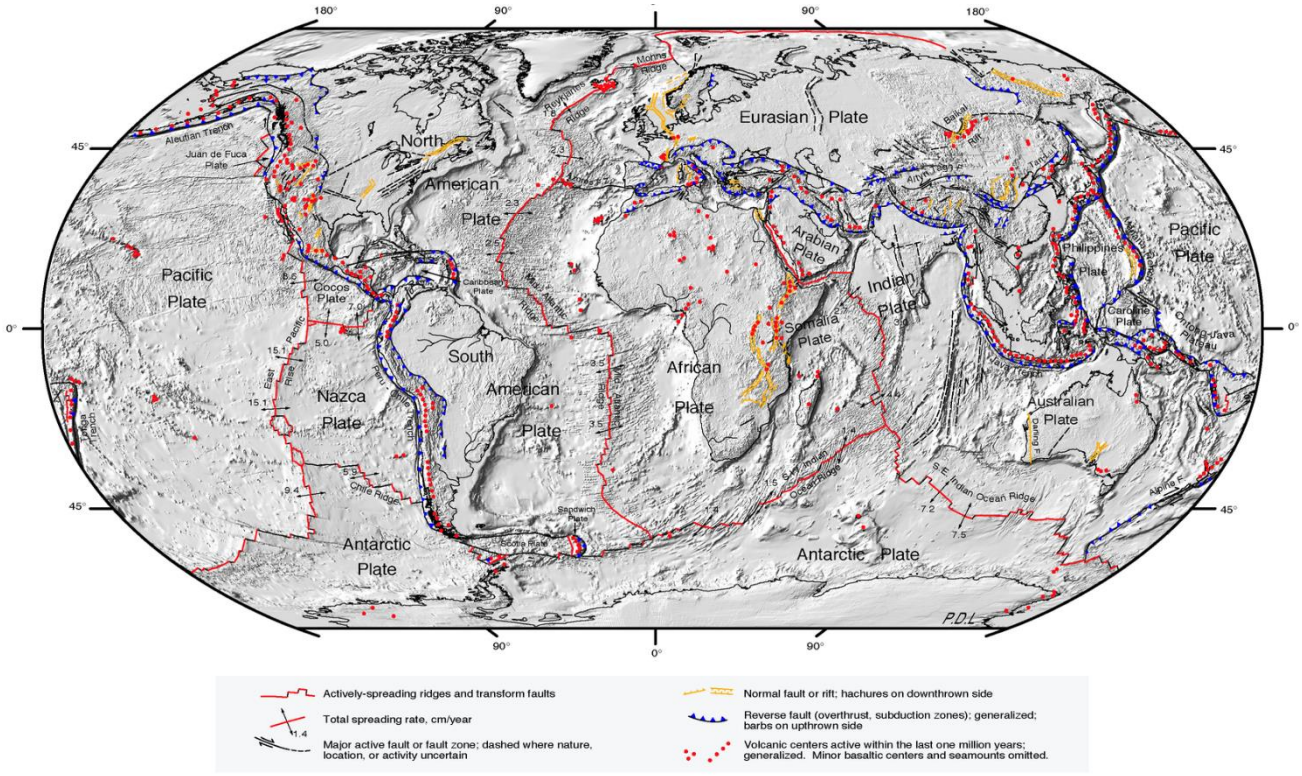

Figure 18 Major tectonic plate boundaries showing tectonic activities of the Earth (Image is curtesy: https://upload.wikimedia.org/wikipedia/commons/b/b4/Plate_tectonics_map.gif)

6.3.2 Types of plate boundaries

The relative motion of the plates along where they meet determines the type of boundary: convergent, divergent, or transform. Earthquakes, volcanic activity, mountain-building, and oceanic trench formation occur along these plate boundaries (or faults). The different types of plate boundaries are shown in Figure 19.

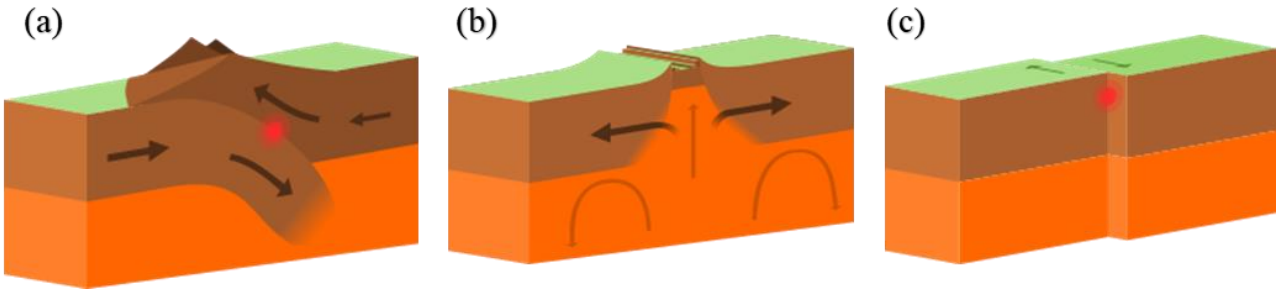

Figure 19 Three types of plate boundaries (a) convergent, (b) divergent, (c) transform

6.3.2.1 Convergent boundaries

They are destructive and occur where two plates slide toward each other to form either a subduction zone (one plate moving underneath the other). At zones of ocean-to-continent subduction (e.g. the Andes mountain range in South America, and the Cascade Mountains in Western United States), the dense oceanic lithosphere plunges beneath the less dense continent. Earthquakes trace the path of the downward-moving plate as it descends into asthenosphere, a trench forms, and as the subducted plate is heated it releases volatiles, mostly water from hydrous minerals, into the surrounding mantle. The addition of water lowers the melting point of the mantle material above the subducting slab, causing it to melt. The magma that results typically leads to volcanism. At zones of ocean-to-ocean subduction (e.g. Aleutian islands, Mariana Islands, and the Japanese island arc), older, cooler, denser crust slips beneath less dense crust. This motion causes earthquakes and a deep trench to form in an arc shape. The upper mantle of the subducted plate then heats and magma rises to form curving chains of volcanic islands. Deep marine trenches are typically associated with subduction zones, and the basins that develop along the active boundary are often called "*foreland basins*". Closure of ocean basins can occur at continent-to-continent boundaries (e.g., Himalayas and Alps): collision between masses of granitic continental lithosphere; neither mass is subducted; plate edges are compressed, folded, uplifted.

6.3.2.2 Divergent boundaries

They are constructive and occur where two plates slide apart from each other. At zones of ocean-to-ocean rifting, divergent boundaries form by seafloor spreading, allowing for the formation of new ocean basin. As the ocean plate splits, the ridge forms at the spreading center, the ocean basin expands, and finally, the plate area increases causing many small volcanoes and/or shallow earthquakes. At zones of continent-to-continent rifting, divergent boundaries may cause new ocean basin to form as the continent splits, spreads, the central rift collapses, and ocean fills the basin. Active

zones of mid-ocean ridges (e.g., the Mid-Atlantic Ridge and East Pacific Rise), and continent-to-continent rifting (such as Africa's East African Rift and Valley and the Red Sea), are examples of divergent boundaries.

6.3.2.3 Transform boundaries

These occur where two lithospheric plates grind past each other along transform faults, where plates are neither created nor destroyed. The relative motion of the two plates is either *sinistral* (left side toward the observer) or *dextral* (right side toward the observer). Transform faults occur across a spreading center. Strong earthquakes can occur along a fault. The San Andreas Fault in California is an example of a transform boundary exhibiting dextral motion.

6.3.2.4 Plate boundary zones

Occur where the effects of the interactions are unclear, and the boundaries, usually occurring along a broad belt, are not well defined and may show various types of movements in different episodes.

6.3.3 The driving mechanism behind Plate tectonics

Tectonic plates are able to move based on the characteristics below:

- the relative density of oceanic lithosphere and the relative weakness of the asthenosphere (Earth's lithosphere has greater *mechanical strength* than the underlying asthenosphere)
- dissipation of heat from the mantle is acknowledged to be the original source of the energy required to drive plate tectonics through convection or large-scale upwelling and doming.
- the current view, though still a matter of some debate, asserts that as a consequence, a powerful source of plate motion is generated due to the excess density of the oceanic lithosphere sinking in subduction zones.
- when the new crust forms at mid-ocean ridges, this oceanic lithosphere is initially less dense than the underlying asthenosphere, but it becomes denser with age as it conductively cools and thickens
- the greater density of old lithosphere relative to the underlying asthenosphere allows it to sink into the deep mantle at subduction zones, providing most of the driving force for plate movement.

The driving forces behind plate tectonics can be divided into three categories based on:

(a) Mantle dynamics- convection currents in the upper mantle are transmitted through the asthenosphere. The results of seismic tomography show a varying lateral density distribution throughout the mantle which manifest as mantle convection from buoyancy forces (Tanimoto & Lay, 2000).

(b) Gravity- Gravitational sliding away from a spreading ridge and mantle doming, slab-pull

(c) Earth's rotation- Tidal drag due to the gravitational force the Moon (and the Sun) exerts on the crust of the Earth; Global deformation of the geoid due to small displacements of the rotational pole with respect to the Earth's crust; Other smaller deformation effects of the crust due to wobbles and spin movements of the Earth rotation on a smaller time scale

The relative importance of each of these factors and their relationship to each other is unclear, and still the subject of much debate.

Exercise

a) List the three classification of seafloor spreading rate and their ranges.

b) Alfred Wegener's hypothesis of continental drift did not gain wide acceptance in the 1920s. Why?

c) Give one difference between oceanic plate and continental plate

d) List 3 types of plate boundaries

e) List 2 driving force behind plate tectonics

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