Our Home, the Planet Earth

A. M. Celâl Şengör

The earth,[1] the abode of the only form of intelligent life in the universe of which we are aware, is a minor member of a system of nine planets, 40 or so moons and about 100 billion asteroids orbiting around the Sun, an average-size member of the 100-billion-star community making up our galaxy, the Milky Way. It is the third planet to the Sun, which it orbits, following an almost circular elliptical path maintaining an average distance of 1.5×10^8 km, with the longest and the shortest radii now being 1.53×10^8 km and 1.47×10^8 km respectively (Fig. 1). This orbit is subject to changes in its "eccentricity" (i.e., in how much it deviates from a circle) with periods of 10^5 and 4×10^5 years (Fig. 2A). In addition, the elliptical orbit itself slowly rotates as shown in Fig. 2B, in what we call the precession.

The earth also has a diurnal rotation, the axis of which is now tilted for 23.5° to the orbital plane (Fig. 1). The axis wobbles (Fig. 2C) and its tilt also varies between 24.5° and 22.1° with a periodicity of about 41,000 years (Fig. 2C). The precession gives rise to a slow shift of the positions of the equinoxes (20 March and 22 September) and the solstices (21 June and 21 December) around the earth's orbit. This "precession of the equinoxes" (Fig. 2D) takes about 24,000 years, which is also referred as a "Great Year." The 100,000-and the 24,000-year periods are now considered to be the prime causes of the ice ages.

The earth has a nearly spherical shape that is slightly flattened

1. The subject treated in this chapter is largely the domain of *physical geology*. The best introduction to physical geology that I am aware of is still Broecker (1985), which assumes only a strong high school background. The *Scientific American* anthologies edited by Press and Siever (1974) and Wilson (1976), and the 1983 *Scientific American* special issue on *The Dynamic Earth*, cover much of the same ground and are recommended to non-earth scientists for further reading. In preparing this article I have consulted extensively, in addition to those just cited, Verhoogen *et al.* (1970), Wyllie (1971), Smith (1981), Anderson (1984, 1989), and Le Pichon (1987), and do not further cite them frequently.

Other studies pertaining to specific topics are cited below only sparingly and have been limited by choice to those that can be understood by a high school graduate.

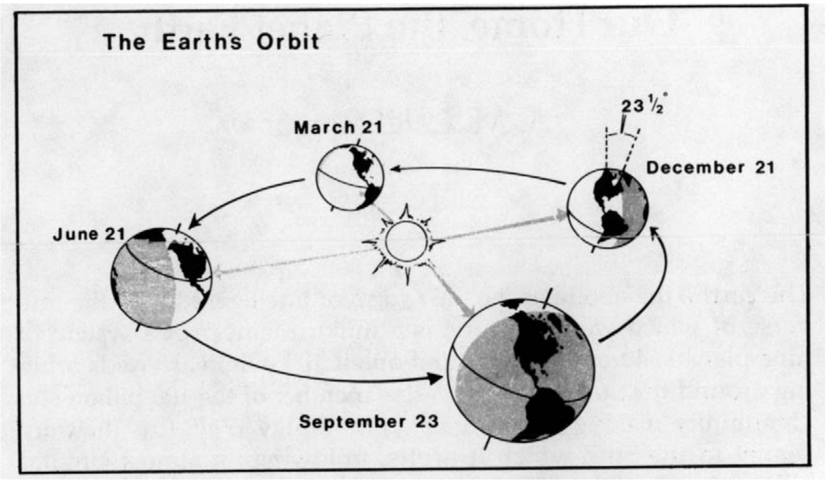

Figure 1: A schematic representation of the earth's orbit around the Sun also showing the 23.5° inclination of the earth's axis to the orbital plane (after Pisias and Imbrie, 1986/87).

at the poles. The ideal shape of this ellipsoidal figure is referred to as a *geoid*. The geoid is the gravitational equipotential surface that coincides with the average level of the sea surface. Its shape is subject to both short-and long-term changes as a function of the diurnal rotational velocity and the distribution of masses both inside and around the earth. At the present, the difference between the lengths of the equatorial and polar radii is only 42 km.

Two factors seem to have had a decisive influence in creating and maintaining the ability of the earth to spawn intelligent life. One is the mass of the earth. It is 6.0×10^{24} kg causing a gravitational acceleration 9.82 m/s^2 at the earth's surface,[2] which has enabled it to hold onto its volatiles. Many of those volatiles make up both the hydrosphere and the atmosphere, the two media in which the earth's biota originated and has since lived and evolved, forming its "biosphere." The other factor is the earth's average distance from the Sun, which allows a range of surface temperatures to reign in which liquid can exist. The surface temperature is also a function of other processes, all of which, however, depend on the presence of water.

The earth is a dynamic body. Not only are the atmosphere and

2. The earth has an average density of 5.52 gr/cm^3 which would have been only 4.3 gr/cm^3 were it not for the gravitational squeezing owing its mass.

https://doi.org/10.1177/039219219103915505 Published online by Cambridge University Press

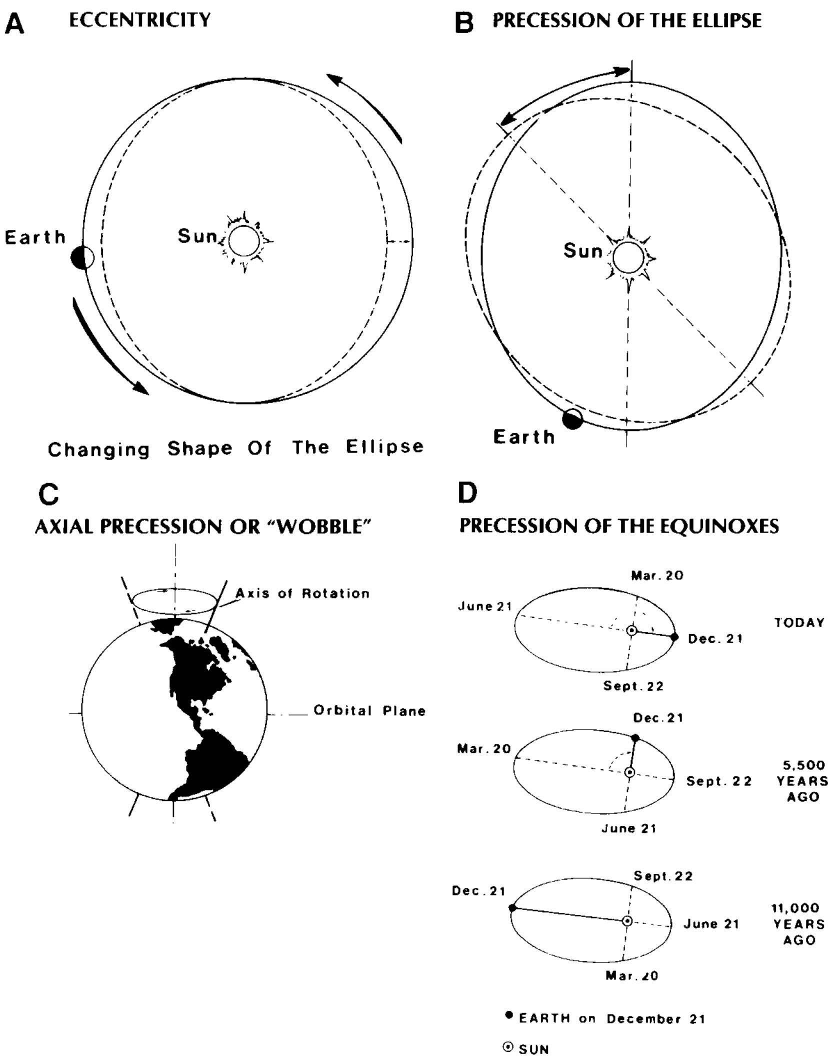

Figure 2: Characteristics of the earth's orbit.

A. Eccentricity of the orbit is subject to variations with periodicities of 10^5 and $4x10^5$ years.

B. The orbit itself rotates ("precesses") around the Sun as shown here.

C. The axis of rotation of the earth wobbles ("precesses") as in the axis of a gyroscope.

D. The combination of all these result in the precession of equinoxes (after Pisias and Imbrie, 1986/87).

the hydrosphere in constant motion, but its outer rocky rind, called the lithosphere, is divided into a number of caps, called plates, that are in constant motion with respect to one another (Fig. 3). Continents are torn apart, opening ocean basins (e.g., the Red Sea), or collide with each other, throwing up mighty mountain ranges (e.g., the Himalaya). Ocean floors plunge into the fiery bowels of the earth along inclined seismic zones, above which volcanic island chains herald the birth of continental material (e.g., the Marianas). What is the cause of this commotion on the face of our planet, a face that has long been a symbol of stability and eternity for our forefathers? For how long has it been going on? What permanent changes did it bring about? How did it affect life, its origin and evolution? What, if any, has been the impact of the changes on the face of our planet on the development of man's thought?

Two different approaches may be adopted to answer these questions. An *ab initio* approach, which tracks the solar nebula from its birth to the present on the basis of what we know (or guess) about the processes that governed its development, seems ideal to understand the broad outlines of the terrestrial evolution by showing us how an object like the earth is made. It is eminently suitable for the very poorly-documented earliest history of our planet, because it starts from the first principles and uses a forward argument. By contrast, a geocentric approach begins with the earth as it now exists and works backwards in time, using mainly the documents its evolution has produced. Naturally, this inverse argument is the ideal way to reconstruct the richly-documented portion of the history of the earth. A measure of success for both approaches is provided by how well their results agree where they overlap.

In the preceding paper I followed the *ab initio* approach to describe the origin and the earliest history of the earth until the formation of those rocks and structure that are today well-preserved, i.e., the interval between 4.6 and 3.8×10^9 years ago. I here change the line of attack, describe the present Earth and go backward in time, discussing on the way the construction of the grand architecture of the terrestrial lithosphere which uses the earth's own energy, and then, how it is sculptured into our landscapes by the so-called "external" processes that exploit the energy of the Sun.

Internal Structure of the Earth and its Earliest Evolution

The present internal structure of the earth provides clues to its earliest evolution during and immediately following accretion. As Fig.

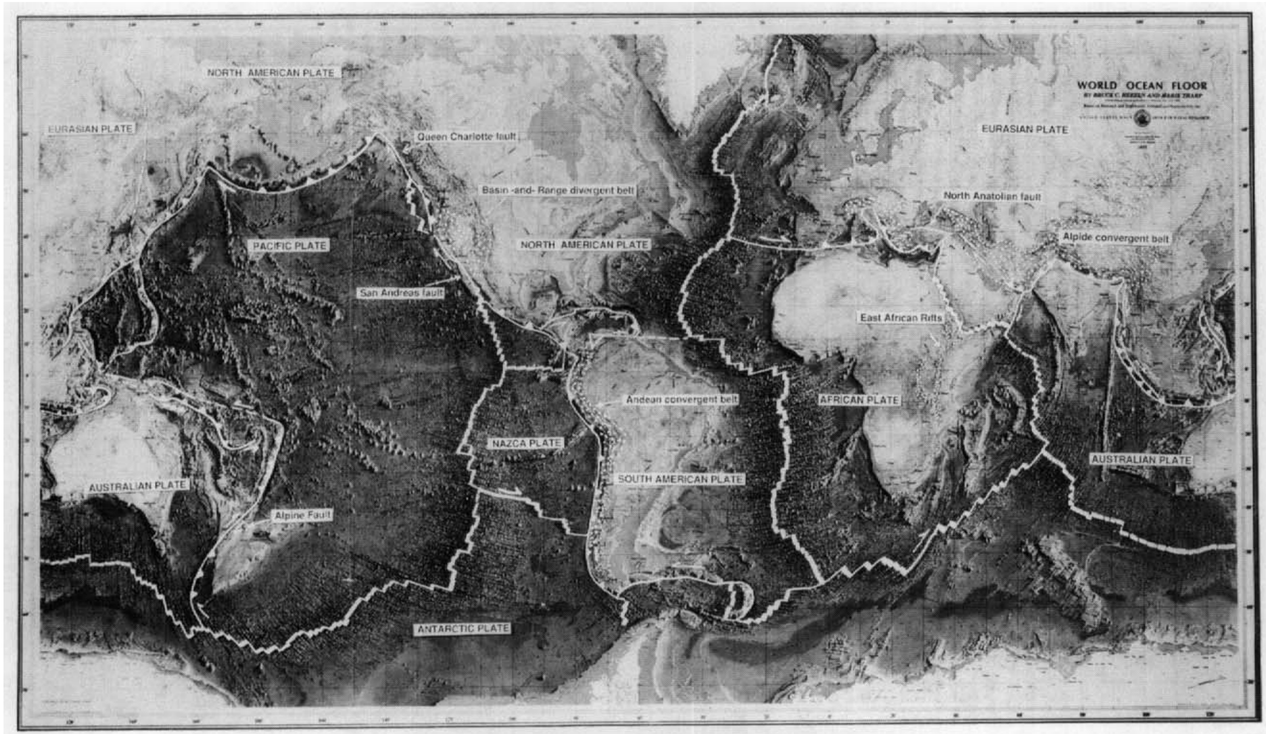

Figure 3: The face of the earth showing its topography and bathymetric (after Heezen and Tharp, 1977) as well as tectonic features (from numerous sources). Note how most plate boundaries coincide with the topographic and bathymetric extremities of our planet (indicating active deformation) and how the wide continental plains and the abyssal plains are away from these. Note also that most major lithospheric plates include both oceanic and continental crust.

https://doi.org/10.1177/039219219103915505 Published online by Cambridge University Press

4 shows, there are three major compositional layers that make up the *crust,* which is defined to be that region of the earth above the *Mohorovicic* discontinuity (*Moho* for short after the Croatian seismologist Andrija Mohorovicic, who discovered it in 1909) separating regions with an average P-wave[3] velocity of 6.5 km/s from those with a velocity of 8.1 km/s^{-1} just beneath it. There are two types of crust on earth today. A 5 to 15 km. thick *oceanic crust* consists dominantly of mafic (i.e., magnesium- and iron-rich) rocks whose compositions are dominated by Mg and Fe silicates, such as basalts and gabbros. The oceanic crust accounts for 60% of the area of the crust and 20% of its volume and 0.00099 of the total earth mass. Under oceanic plateaux that make up 10% of the area and probably nearly 50% of the volume of the oceanic crust its thickness may become as large as 30 km. The mean age of the oceanic crust is 0.1 billion years, and its greatest age is about 0.2 billion years. The other crustal variety is the *continental,* whose average thickness range of 30 to 50 km may swell to 80 km under some mountainous regions such as Tibet and the Himalaya, and which makes up 0.0374 of the total earth mass. It consists mainly of Al silicates that give it an average composition of an andesite (a volcanic rock – named by Leopold von Buch after the Andes – with an SiO_2 content varying from about 55% by weight to about 63%). The continental crust has an average age of about 2 billion years, with its oldest fragments being older than 3.8 billion years. Some authors (e.g., Anderson, 1989) also recognize a *transitional* crust between the continental and the oceanic that makes up some island arcs, continental margins, and a few oceanic plateaux such as the Kerguelen plateau in the Indian Ocean. The thickness of the transitional crust ranges from about 15 to 30 km. The average density of the continental crust is around 2.8 gr/cm^3. This results in a double-peaked hypsometric curve showing the frequency distribution of elevations for the surface of the earth, as the lighter and thicker continental crusts "floats" higher than the thinner and heavier oceanic crust on the underlying mantle (Fig. 5). That figure also shows how the altitude differences influence the distribution of

3. Earthquakes, i.e, ruptures in the earth's stony layers, produce two kinds of waves. P-or primary (or "pressure") waves oscillate in the direction of their propagation and "press" onto obstacles in their way. The S-or secondary (or "shear") waves oscillate at right angles to propagation and "shake sideways" the medium in which they travel. Thus, the S-waves cannot propagate through a liquid medium. The denser a medium, the faster the two kinds of waves will travel through it.

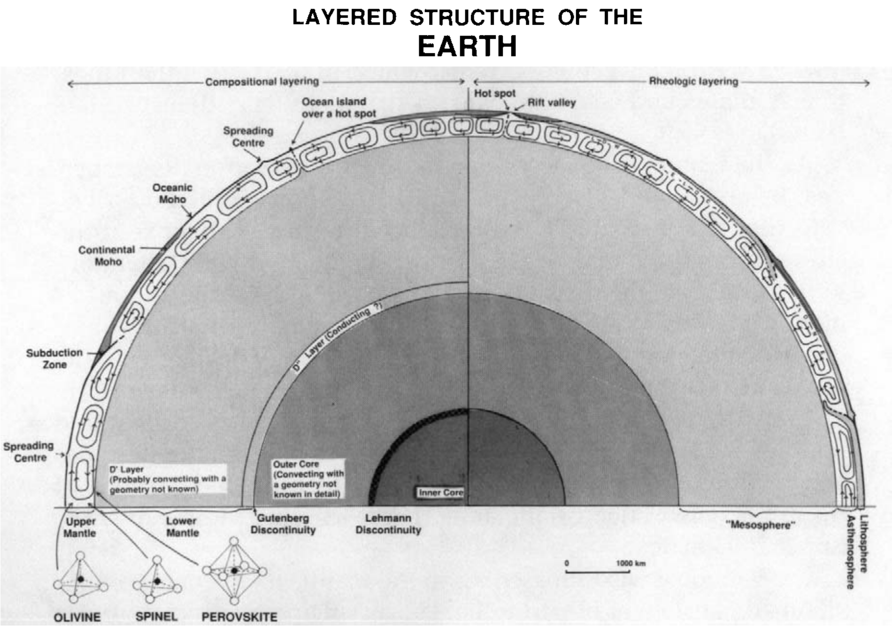

Figure 4: The layered structured of the earth. To the left, the chemical layering. To the right, the rheological layering defined by the manner in which the material is deformed.

organisms on the face of the earth. Fig. 6 shows the distribution of the two types of crust on the face of the earth.

Beneath the crust is the earth's *mantle*, which extends down to a depth of about 2900 km, where the P-wave velocity drops sharply from about 13.6 to about 8.0 km/s along a boundary known as the Gutenberg discontinuity (after the German seismologist Beno Gutenberg, who discovered it in 1912 by improving an earlier study by the Irish geologist Richard Dixon Oldham, which had demonstrated that the earth had a core in 1906). The earth's mantle consists dominantly of magnesium silicates, but the mineral in which this composition is largely accommodated is disputed (Anderson, 1984). It accounts for nearly half of the earth's radius, 83% of its volume, and 67% of its mass. It represents the main reservoir from which the chemical components of the crust, oceans, and the atmosphere have been differentiated. And by degassing, it has produced the gaseous carbon compounds that have provided the raw material for organic molecules and CO_2 "thermostat" that prevents a complete freezing of the earth's surface. Temperature

https://doi.org/10.1177/039219219103915505 Published online by Cambridge University Press

differences in the mantle drive giant and very slowly moving (a few cm/year) convection currents, which in turn drive the lithospheric plates and cause volcanism that is independent of plate boundaries.

As the mantle is not accessible to direct observation, its properties, behavior, and history are studied by indirect methods. The velocities of the seismic waves produced during earthquakes travelling through the mantle are used in conjunction with laboratory tests to estimate the densities and to calculate the compositions of mantle materials. These results are then compared with those of experimental petrology (i.e., the branch of geology dealing with the origin of rocks) and geochemistry to provide further information. The few direct observations on mantle materials all are confined to nodules brought to the surface by volcanoes and kimberlite pipes and to rare outcrops in mountain belts which expose portions of the immediately subcrustal mantle. These together sample only the upper 200 km or so.

Conventional wisdom ascribes to the mantle an average composition similar to that of peridotite, i.e., an olivine-rich rock (peridot is the name given to gem-quality olivine), dominated up to 90% by weight by SiO_2, MgO, and FeO. Al_2O_3, CaO, and Na_2O together make up some 5 to 8% and no other oxide reaches a concentration exceeding 6%. In the uppermost reaches of the mantle (~ 150 km or so) 0.1% H_2O probably is accommodated in such hydrous minerals as phlogopite (a mica) and amphiboles (Wyllie, 1975).

Propagation velocities of seismic waves help to distinguish three major regions in the mantle. An upper mantle extends from the base of the crust to about 400 km in depth. The dominant mineral in this part is thought to be olivine in classical olivine tetrahedral form (Fig. 4). An upper low velocity layer (called the *low-velocity zone* or *LVZ*: well-established for the S-waves, less so for P-waves) may be due to limited partial melt forming thin films of liquid between mineral grains. Recent improvements in the precision of the seismic date indicate, however, that along certain preferred directions in the LVZ (notably parallel with plate motion direction) seismic wave propagation may be faster and they can be explained without invoking partial melting. Beneath the LVZ, seismic velocities increase markedly to 400 km in depth.

The region between 400 and 650 km is called the *transition zone* and is commonly believed to consist mainly of olivine in a tighter tetrahedral arrangement called the spinel structure (Fig. 4).

The 650-km discontinuity[4] is much sharper than the one at 400 (because it is a good reflector for seismic waves) and may occur over a thickness of only 4 km. No earthquakes are known beneath 690 km, and plates that plunge into the mantle penetrate the layer below only rarely and with much difficulty (Fig. 4). On the basis of this observation some geophysicists have concluded that the mantle in the first ~ 700 km convects independently of the lower mantle (e.g., McKenzie and Richter, 1976; McKenzie, 1983). This view has been strengthened recently by two independent observations. One concerns the ratio of the isotopes Nd^{143} to Nd^{144} in the crust. This ratio is measured to be such that about half the volume of the present mantle appears to have supplied Nd^{144} to the crust, so that the Nd^{143}/Nd^{144} ratio has contributions both from the decay of the radioactive isotope Sm^{147} and from the primeval Nd abundance as calculated on the basis of the abundances in the carbonaceous chondrites. The other observation is on variations of satellite-measured sea-surface elevation that can be converted to extremely high resolution gravity anomalies. These show that convection cells with a ~ 1000 km separation between cold sinking limbs and hot rising limbs do exist in the mantle (e.g., McKenzie, 1983). These observations support the interpretations favoring a fairly complicated and a temporally unstable two-scale picture of the convection in the upper 700 km of the mantle. One scale corresponds with the scale of the plates themselves, where the rise to sink distance may be as large as 10,000 km seems superimposed on a smaller scale circulation in which roughly equant cells locally may be drawn out into cylindrical shapes under the influence of moving plates. But a high degree of decoupling along the LVZ enables the second-order cells largely to retain their roughly equant shapes.

The energy to drive this double-scale convection is provided both from below, from the lower mantle, and from within, from the decay of the radioactive isotopes of uranium (U), thorium (Th), and Potassium (K). Continents form very efficient insulators and as a result the temperature of the upper mantle under them rises, diminishes the velocity of seismic waves (i.e., the density), and thus expands and uplifts the mantle, creating geoid highs. By con-

4. The upper mantle above the 650 km. discontinuity is in places referred to as the asthenosphere (from the Greek ασθενης = weak, without resistance) because it yields more easily than what lies below (also called the mesosphere, i.e. the "middle" sphere) and above (Fig. 4). Some authors restrict the asthenosphere to about 400 km. and some use it interchangeably with the LVZ low velocity zone.

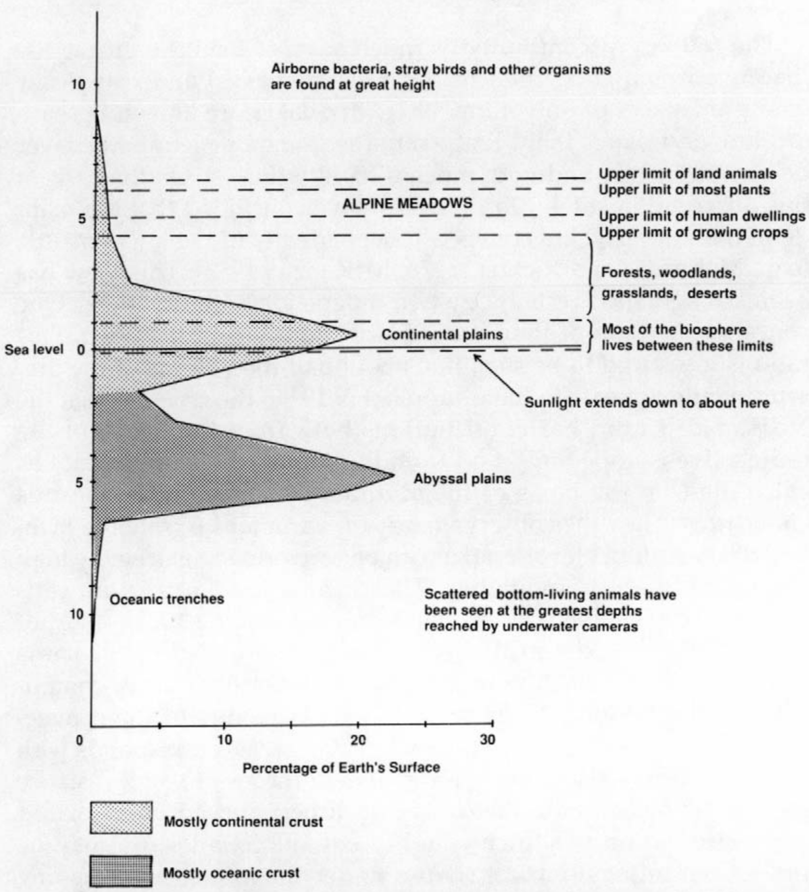

Figure 5: The hypsometric curve of the earth, on which is plotted the distribution of organisms. (Adapted from Skinner and Porter, 1987.)

trast, large and long-lived subduction zones cool the mantle, contract and subside it, and increase the seismic velocities. These zones correspond with the geoid minima. The displacements of masses change the inertial movement of the earth and have caused the real migration of the poles (Anderson, 1984).

The independently convecting upper 700 km of the mantle also provides an effective insulator for the lower mantle, in which an independent convective circulation is probably operative. An about 200 km thick upper layer is called the D' shell and the lower-most 200 km constitutes the D'' shell. The composition of the lower mantle has been viewed generally to consist mainly of "olivine," but in a very dense perovskite structure where 6, instead of only 4, O atoms surround one Si atom (Fig. 4) plus (Mg Fe)O. However, if the adiabat (i.e., zero heat exchange) temperature is only 200°C higher, which seems likely, a chondritic or pyroxenitic composition may be more appropriate (Anderson, 1989).

In only very few places material seems to leak from the lower mantle into the upper mantle. This material is identified on the basis of its isotopic ratios. For instance, the isotopic ratios of volcanic rocks that have erupted in Hawaii are intermediate between those found along midocean ridges (i.e., "upper mantle sourced") and those that ought to be characteristic of the "bulk earth," i.e., fed from a reservoir isolated from the upper mantle for about a billion years. The only reservoir that probably has these characteristics is the lower mantle. This material seems transferred from the lower mantle to the upper mantle through boundary perturbations under the rising jets of the small-scale convective cells of the upper mantle (Fig. 4), called "hot-spots" in the geological literature (Burke and Wilson, 1976; White and McKenzie, 1989).

The Gutenberg discontinuity separates not only a solid mantle from a liquid outer *core*, but also represents a sharp chemical boundary. Our knowledge of the physics of the earth's core comes mainly from seismology and geomagnetism, which are supplemented by considerations of the earth's bulk chemistry based on the cosmic abundance of the elements and on comparisons with the iron meteorites to surmise its possible composition (Jeanloz, 1983). Despite claims to the contrary by some, no samples of the core have become available for direct observation.

In 1936, the Danish geophysicist Inge Lehman noticed that in order to account for some particular phases of the seismic waves of an earthquake along the Alpine Fault in New Zealand, which were observed at the epicentral distances greater than 120° with travel times 18 to 20 minutes, an inner solid core of a 1200 km radius had to be assumed. The so-called Lehman discontinuity between a liquid outer core and a solid (or perhaps very viscous) inner core is actually a zone of transition across which the P-wave velocity increases from 10.2 to 11.2 km/s (Fig. 4).

Most extreme conditions prevail in the core. Pressures range from 1.3 to 3.5 million atmospheres, while temperatures range from 3700°C at the Gutenberg discontinuity to almost 7000°C! Both

https://doi.org/10.1177/039219219103915505 Published online by Cambridge University Press

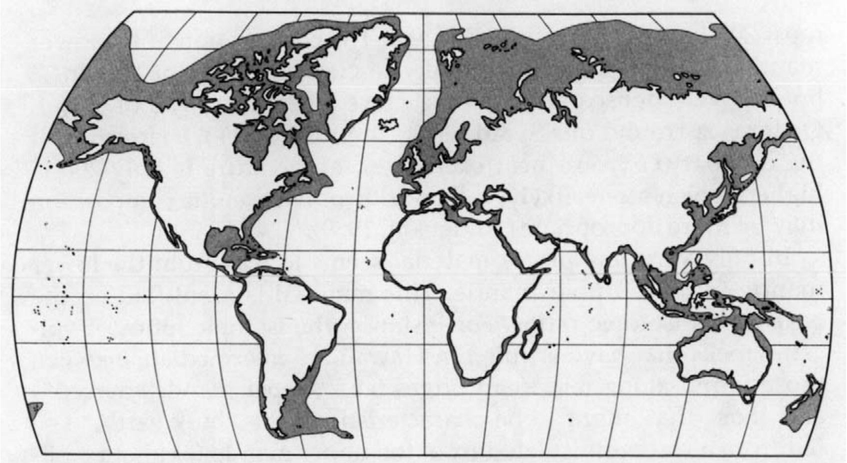

Figure 6: Map showing the distribution of continental and oceanic crust on earth. Continental shelves, shown in grey, are continental (after Skinner and Porter, 1987).

the inner and the outer regions of the core are believed to consist dominantly of Fe with a little Ni because: 1) it has to be a good electrical conductor, 2) it has to be denser than at least 10 gr/cm^3 (more than 6.0 gr/cm^3 at zero pressure), and 3) no element other than Fe that could satisfy 1 and 2 has high enough a cosmic abundance to be a candidate. However, the density, especially of the outer core (9.9 gr/cm^3 at the core-mantel boundary) is less than that of liquid Fe at comparable temperatures and pressures (10.8 gr/cm^3). This implies that a small amount (~ 8–10%)of less dense components such as S, O, or Si may have alloyed with the Fe. Such alloys would have a melting point lower than that of pure Fe. This further supports the presence of less dense components in the outer core, because the temperature of the outer core is thought to be below the melting point of pure iron.

The presence of convection currents have been postulated to generate a self-exciting dynamo in the outer core that creates and maintains the earth's magnetic field (Fig. 7). 90% of this field is bipolar (similar to a bar magnet oriented parallel with the earth's axis of rotation), and 10% is multipolar. The convective motions of the liquid outer core are affected not only by the earth's rotation (the coriolis effect) but also by the relatively high Rayleigh number (i.e., the ratio between the forces that accelerate a fluid and the viscous forces that retard it) that probably leads to turbulence in the flow. The chaotic nature of the flow now and then reverses the

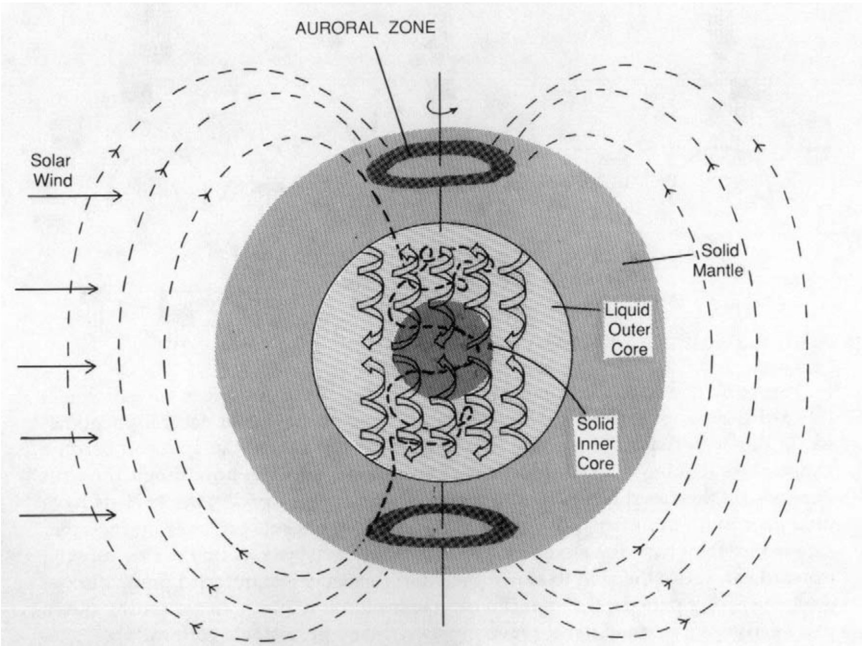

Figure 7: A highly schematic view of the earth's core and the magnetic field it creates. (Adapted from Jeanloz, 1988.)

dynamo and the earth's magnetic field flips over in an interval of a few thousands of years to create what are known as geomagnetic reversals, much like a Lorenzian waterwheel (Fig. 8). The intervals between two reversals have been irregular in the past.

Currently there are two competing opinions as to what maintains the convective circulation in the outer core. The traditional view ascribes it to thermal differences fueled in part by enough U and K that may have partitioned into the core, in part by the original gravitational energy that was released when the earth originated, and in part by a possible heat source liberated during the crystallization of the inner core. A more recent views ascribes it to compositionally driven density differences. The two models are not mutually exclusive and it is very likely that some sort of thermal convection does help to cool the outer core and supplies heat to the lower mantle.

Magnetization of old surface rocks suggests that a geomagnetic field of about the same intensity as the present one existed at least

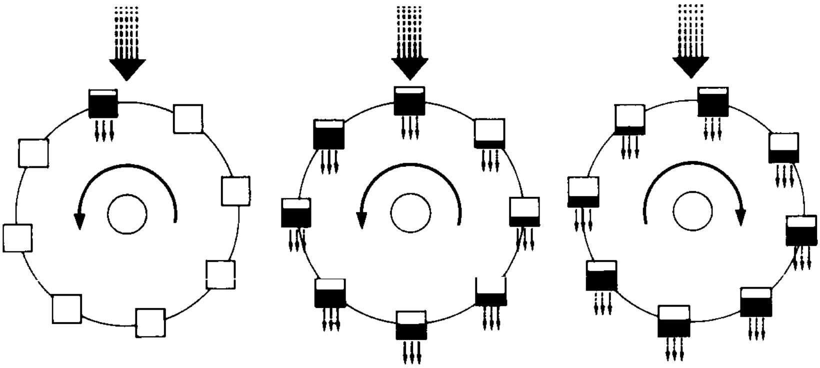

Figure 8. The Lorenzian waterwheel, named after the American meteorologist Edward Lorenz, one of the co-discoverers of chaotic behavior of natural phenomena. In this waterwheel, if the flow of water at the top is fast, the spin can become chaotic. As leaking buckets pass under the flowing water, how much they fill depends on the speed of the spin. If the wheel is turning rapidly, the buckets have little time to fill up. Also, if the wheel is turning fast, buckets can start up the other side before they have time to empty. As a result, heavy buckets on the side moving upward can cause the spin to slow down and then reverse. In fact, Lorenz discovered, over long periods, the spin can reverse itself many times, never setting down to a steady state rate and never repeating itself in any predictable pattern.

This waterwheel is a perfect mechanical analogue for the self-reversing convective circulation of the outer core, where the fast water flow on the top simulates the heat flow. Notice that no changes in heat input are necessary to induce irregular reversals of convective circulation.

2.5 billion years ago and probably existed 3.5 billion years ago, suggesting that the earth's core in its present configurations at least equally as old. However, arguments on the basis of the relative abundances of Pb and Xe isotopes in the rocks suggest that the earth's core must have formed already during the first 0.1 billion years of its history. The conventional wisdom now is that the core formation probably started by the time the earth was 1/8 of its present size, and that it was essentially complete very shortly after the earth had formed. The formation of the core would have released a gravitational energy equivalent to heat dissipated by the whole earth for 4.6 billion years. This would be enough to melt and differentiate the planet into its layered structure that now exists.

The great importance of the core and its magnetic field for the surface conditions on earth is, apart from the magnificent aurora borealis, that it shields the surface from lethal doses of solar radiation and may also influence climate.

Plate Tectonics[5]

Presently, the earth's lithosphere, i.e., that part of the crust and upper mantle that deforms elastically for the load and timescale in question (generally 10 to 100 km thick: Fig. 4) is divided into a small number of quasi-rigid caps that are constant motion with respect to one another (Fig. 3 and 4). Three kinds of boundaries separate these caps which are called *plates* (because they occupy immense areas compared with their modest thickness). Along *divergent boundaries* two plates move apart, and most commonly, new materials in the form of new oceanic crust and upper mantle are generated and added to the separating plates in a bilaterally symmetric fashion with respect to the divergent boundary through a process called *sea-floor spreading*. Mid-oceanic ridges are the most important representatives of the divergent boundaries which are also known as spreading centers. Along *convergent boundaries* two plates approach one another, and oceanic ones descend into the mantle asymmetrically along *subduction zones* which appear as ±50 km thick inclined seismic zones in places reaching as far down as the 650 km discontinuity in the mantle (Fig. 4). Surface expressions of subduction zones are commonly oceanic trenches flanking volcanic island arcs or large continental margin mountain belts such as the Andes of South America (Fig. 3). Where two plates move past one another parallel with the boundary, neither plate destruction nor plate generation occurs. Such boundaries are marked with large stripe-slip faults and are termed *conservative boundary*. As seen in Fig. 3, such strike-slip faults usually transform the plate motion from one type of boundary to another (e.g.,the San Andreas and the Queen Charlotte faults in Fig. 3), which is why they have been called *transform faults*. The three types of plate boundaries form a continuous network of mobile belts on the earth's surface and localize more than 95% of its seismicity. Shallow earthquakes (focal depth <60 km) characterize exclusively the divergent and conservative boundaries, where nearly all earthquakes are shal-

5. Tectonics (from the classical Greek η Τεκτονικη, "skilled in building; carpenter") is that branch of geology which studies the architecture and structural evolution of the earth's outer rocky rind, the lithosphere, and the forces that bring this evolution about. It also refers to the geological structure of a given area. Plate tectonics refers both to the plate structure of lithosphere and to its study.

For a semi-popular introduction to plate tectonics, see Dewey (1972). Of the more detailed recent accounts Cox and Hart (1986) emphasize its kinematic aspects, Park (1988) and Condie (1989) the geological corollaries, and Fowler (1990) the geological aspects. Menard (1986) gives an excellent history of the concept.

lower than 30 km. Shallow, intermediate (between 60 and 450 km), and deep (450 to 690 km) earthquakes are associated with convergent boundaries. Continents move embedded in plates, like ships frozen into drifting ice-floes. Continental drift is a consequence of the plate movements.

The present-day locations of plate boundaries and the current plate motions are known from earthquake focal mechanisms (i.e., from a knowledge of the direction of slip along a break during an earthquake) and from geodesy. A noticeable feature of the map shown in Fig. 3 is how narrowly confined earthquake belts are in the oceanic lithosphere (coincident with the plate boundaries), in contrast to the tremendous scatter seen in the continental lithosphere (e.g., western U.S., central Asia, east Africa: shown with stippling in Fig. 3), regardless of the type of plate boundary. This results from the difference in composition of the two types of crust. The continental crust is SiO_2-rich (~ 60% by weight), whereas the oceanic crust (~ 50% by weight) is not. Thus, the continental crust has a low shear strength like quartz, while the oceanic crust is more resistant to shear deformation. Also, continents are buoyant (i.e.,they normally do not get subducted), whereas subduction is the usual fate for ocean bottoms.

A wide range of specific geological processes are associated with plate boundaries, whose record in the geological past enables us to reconstruct former plate boundaries and erect a history of motions of the earth's surface, which are not only interesting from the view point of those who inhabit that surface, but also because they yield valuable clues concerning the evolution of the deeper layers of the planet.

Divergent boundaries originate in continents commonly when the continent lies on a hot region in the mantle (likely caused by continental insulation itself) that also forms a geoid high. Both vigorous convective upwelling ("hot spot") and the gravitational potential associated with the high tear the continent asunder. The initial products of such tearing are multi-branched, normal-fault-bounded troughs called rift-valleys, such as those that exist in East Africa now (Fig. 3). Such rift valleys commonly are sites of volcanism that directly tap the upper mantle (Fig. 9B). Stretching thins the crust, the surface of which subsides, owing to thinning above the hot upwelling mantle material. This upwelling also thins the lithosphere considerably. Finally, the continent breaks apart and sea-floor spreading begins creating an ocean (Fig. 9C).

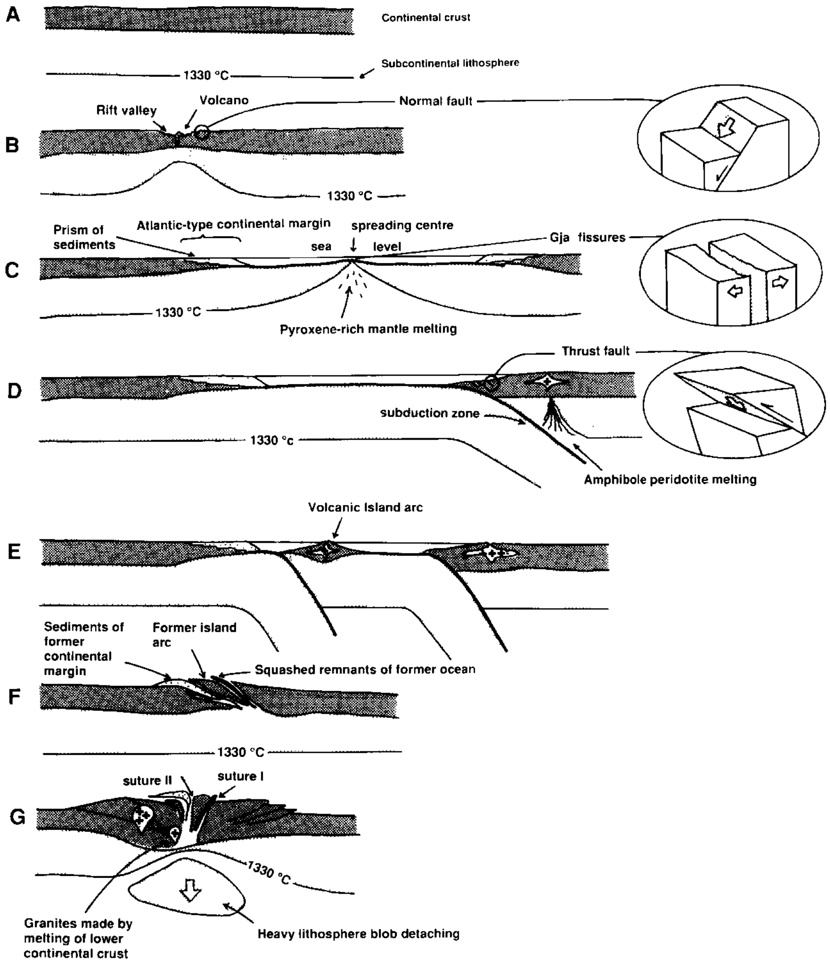

Figure 9: A cross-sectional representation of the "Wilson Cycle." A. Normal continental lithosphere, undeformed. B. "Rifting" creates a divergent plate boundary along a rift valley characterized by normal faulting and volcanism. C. Sea-floor spreading along the divergent boundary creates an ocean flanked by Atlantic-type continental margins. D. Plate convergence creates a subduction zone along which the ocean floor returns to mantle and causes partial melting. E. Final stages of the closure of an ocean. Depicted here is also an intraoceanic "exotic" island arc. F. Ocean closed. Note that "exotic" island arc in the final architecture of the collision-induced mountain-belt would be hard to interpret with respect to its former affiliation with either of the continents. G. "Intracontinental" convergence has led to further crustal and lithospheric thickening. A large cold lithospheric root becomes unstable and is detached, sinking into the less dense asthenosphere. The resulting abrupt rise of the 1330°C isotherm may induce partial melting within the crust and lead to further differentiation.

Along the spreading centers oceanic crust is accreted along an extremely narrow zone (<10 km) by repeated injection of red-hot basaltic lava along the axis into fissures opened by the continuous divergence of the two plates (see Fig. 9C; these fissures are known as *gjá* fissures in Iceland, where they can be seen subaerially). Fe-bearing magnetic minerals become aligned parallel with the earth's prevailing magnetic field in the spreading centers and as the lava cools below what is known as the Curie temperature (generally between 600°C and 400°C), it acquires a weak magnetization, which is completely "frozen in" by the time a basaltic lave has cooled 50°C below its Curie temperature. Because the earth's magnetic field reverses irregularly, variously magnetized bands of diverse width stripe the ocean floor parallel with the spreading centers and provide a means to reconstruct the past geometries of such centers (Fig. 10). Because it is possible to date the magnetized igneous rocks by isotopic methods, a reversal time-scale can be constructed that also yields a velocity for sea-floor spreading. For example, the Atlantic Ocean has been expanding with a full spreading velocity of 2.5 cm/yr, whereas the east Pacific Rise has a full spreading velocity of nearly 16 cm/yr.

Nearly all spreading centers now stand about 2.5 km below sea-level, and ocean floor subsides away from them, following an exponential curve so regular the world over that it has become possible to estimate the age of a piece of ocean floor simply by measuring its depth (Fig. 11). This regular subsidence is a function of the cooling of the lithosphere as it travels away from the hot spreading centers. When the lithosphere is about 80 million years old, the convective heating of its bottom and heat loss from the top balance out, and the thermal subsidence ends.

Continental margins created by rifting and subsequent sea-floor spreading (called "Atlantic type" by the Austrian geologist Eduard Suess in 1888, owing to their dominance around the Atlantic Ocean) also subside according to a similar curve and consequently accumulate a prism of sediments (Fig. 9C). Along such old continental margins of this type (e.g., the Atlantic margin of North America) sedimentary thickness may reach 17 km! A part of this thickness is due to subsidence under the load of the sediments deposited during the thermal subsidence phase. Sedimentary prisms deposited on Atlantic-type continental margins are among the prime places for the generation and storage of the world's hydrocarbon reserves.

In places where plate kinematics dictates that two plates converge, subduction zones commonly form (Fig. 9D). Continental margins formed by subduction processes (e.g., western South Africa) are also called "Pacific type," according to Suess. Diverse effects contribute to their localization, but it is axiomatic that old, cold, dense oceanic lithosphere dips into the upper mantle more easily than young, hot, less dense oceanic lithosphere. Much water is dragged down along subduction zones in hydrous mineral phases of both igneous and sedimentary origin (amphiboles, micas, various hydrous carbonates, and oxides). As they descend into the hot and high-pressure regions of the mantle, the relaxed mineral phases convert into more compact ones, releasing their H_2O, which ascends vertically into the overlying mantle wedge, depressing its melting point and triggering partial melting. A hydrated mantle melts, among other things, amphiboles, and these generate the typical magmatic rocks building island arcs. These rocks are andesites (see above), whose composition is similar to the composition of the bulk continental crust.

So, while clinopyroxenes from the mantle are the main contributors to the source of oceanic basalts, pyroxenes + H_20 (=amphiboles) seem to be the main contributors to the generation of the continents. H_2O is therefore a critical component in the plate tectonic cycle that eventually makes continents from a dominantly ultramafic mantle! Also, the calcium carbonate ($CaCO_3$) in the subducted sediments reacts with sedimentary SiO_2 (usually in the form of deep sea cherts) to release CO_2 into the atmosphere through island-arc volcanism. As I mentioned above, this CO_2 cycle forms a very efficient thermostat to prevent the earth from freezing (Broecker, 1985).

When two continents collide across a convergent boundary (Fig. 9F), buoyancy inhibits subduction, and the displacement is converted into distortion (called strain) of the two continents, which literally scrunch together along the convergent boundary (Fig. 9E and F). This scrunching creates lofty mountain ranges such as the Himalaya along the collision front, called a suture. As the mountains rise the lithosphere thickens, and more of it is plunged into the underlying asthenosphere in the form of a root (Molnar, 1986). This root then melts (as it descends into regions hotter than its normal level of residence), which also partially melts the overlying continental continental crust and differentiates it into an upper, SiO_2 and volatile-rich crust and a lower, mafic, more refractory crust. This sort of a double-layered continental crust is the final, indestructible product of the plate tectonic cycle.

One question that immediately arises is why the continents are not 50–80 km thick, as they are in active collision zones (e.g., from the Alps to the Himalaya), but are typically 30–50 km. There are two main reasons for this. One is that a continent higher than about 4–5 km with respect to the ocean floors tends to spread out under its own potential energy like a lump of silly putty left on flat surface. This is especially true for the very high mountainous areas such as the Himalaya and Tibet (average height above the ocean floor ~ 10 km). This process can return a thick crust to a normal thickness within a few million to few tens of million years (Molnar, 1986).

The other mechanism is subaerial erosion (Pitman and Golovchenko, 1991). External agencies such as wind, rain, and snow that derive their energy from the sun's heat incessantly wear down what plate tectonics have created. Especially H_2O, in the form of sheet floods, streams, rivers, glaciers, and waves, constantly chip away the land surface, transport the resulting debris, and eventually deposit it in the sea. This erosive activity gradually denudes the land surface, and, if left to its own means, would wear it down to sea-level. But this is a very slow process. If base level (i.e., sea level) remains stationary, it would take several hundreds of millions of years to denude a mountain belt to sea-level (Pitman and Golovchenko, 1991).

Plate Tectonics in Earth History: The Wilson Cycle

In 1968, the great Canadian earth scientist J. Tuzo Wilson pointed out that if plate tectonics has been going on for an appreciable portion of the earth history, historical geology would be nothing more than a continuous procession of opening and closing of oceans (Fig. 9A–G). Because this cycle (since called the Wilson cycle) not only determines the shape of the oceans but also their bathymetry and topography of the continents, its record constitutes almost the whole of the geological history of our planet. As plates move about, they also go on generating continental material and thus enlarging the continents.

The earth's history has been divided by geologists into four major subdivisions called eons (Table 1). The first eon, called the Priscoan,[6] is applied to times for which we have no geological

Table 1: The eons in Earth history

Eon	Beginning	End
	(in millions of years before present)	
Phanerozoic	570	–
Proterozoic	2,500	570
Archaean	4,000	2,500
Priscoan	?4,600	4,000

record, owing to later destruction by subduction and/or meteorite impact, and spans the time interval between the earth's accretion and 4 billion years ago. The second, called Archaean,[7] between 4 to 2.5 billion years ago, was a time when the earth was a little hotter than today (the lavas erupting at the surface were some 200°C hotter than the hottest now erupting), plates were probably smaller and may have been moving six times faster (probably because convection was more vigorous in a hotter earth), and there were no major continents, at least not with their present SiO_2 dominated composition. The most sophisticated life probably was yet only in bacterial form. The third eon, the Proterozoic,[8] between 2.5 and 0.59 billion years ago, witnessed the growth of the continental crust almost to its present size, cooling of the earth, and a slowing down of plate motion, perhaps to its present average value. The final, the Phanerozoic[9] eon, in which we are living, spans the last 1/9th of early history, but it is the interval best studied and best understood. Following a tremendous, explosive diversification of life forms between 0.57 and 0.51 billion years ago,[10] most of the major life forms we know today evolved in the Phanerozoic, culminating some 3 million years ago in an intelligent creature called "Man."

The Phanerozoic has not been all that different from the Proterozoic in terms of behavior of the planet except for the

6. From the Latin priscus (ancient, primitive).
7. From the Greek αρχη (beginning, origin).
8. From the Greek προτερος (prior) and το ςωον (living being, animal).
9. From the Greek Øανερος (visible, manifest, evident) and το ζωον.
10. For a most readable account of this explosive diversification of life right at the beginning of the Phanerozoic eon see Gould (1989). This magnificent book also constitutes an excellent expositor for the rule of "chance" in evolution of both the earth and its inhabitants. Its extremely important implications for epistemology are somewhat marred by Gould's inadequate understanding of Popper's views.

https://doi.org/10.1177/039219219103915505 Published online by Cambridge University Press

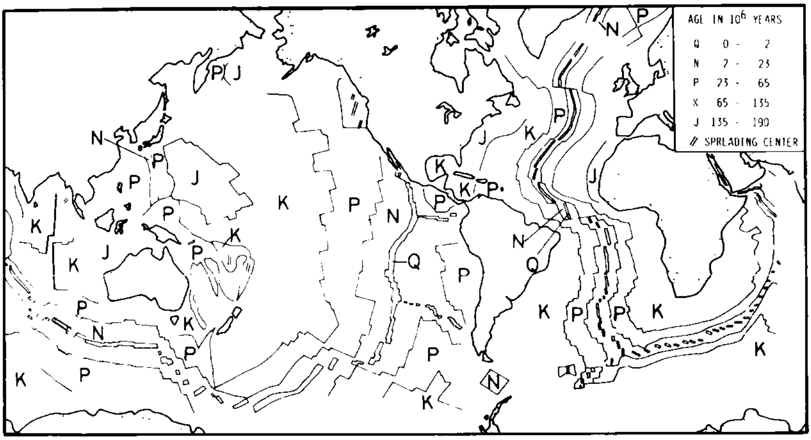

Figure 10: Oceans age away from spreading centers in a bilaterally symmetric pattern measured by the symmetric disposition of magnetic anomalies. Note how, by matching the boundaries of the age provinces, one may reconstruct the past geometries of the oceans and hence of continental drift. (After Uyeda, 1983.)

immense diversity provided by the higher organisms, especially plants. Continental movements increased their influence on the circulation in the oceans and on climate as the continental crust grew. At times of maximum continental dispersion, especially when east-west seaways communicated with north-south ones, the earth had a milder climate than when supercontinents blocked east-west oceanic circulation.

A major control that plate tectonics have exercised on the external processes of denudation and deposition has been through the control of sea level.[11] This control is exercised dominantly through plate motion rates. Owing to the time-dependent thermal subsidence of the ocean floors, faster plate motion rates generate broader mid-ocean ridges (Fig. 11B) and thus diminish the capacity of ocean basins, causing their water to "spill over" onto the continents (these "spill-overs" are called *transgressions*, as the sea transgresses onto land surface). By contrast, a slow global plate motion rate reduces the volume of the mid-ocean ridges and increases the capacity of the ocean basins, thus causing withdrawal of the sea from continental interiors which we thus speak of as *regression*.

11. The history, magnitudes, and cause(s) of global sea-level oscillations (called eustatic movements by Suess in 1888) have been rather heavily debated in the last decade and a half. This field and the associated controversies have been developing so rapidly, however, that it is difficult to paint a concise and accurate picture of the current situation here.

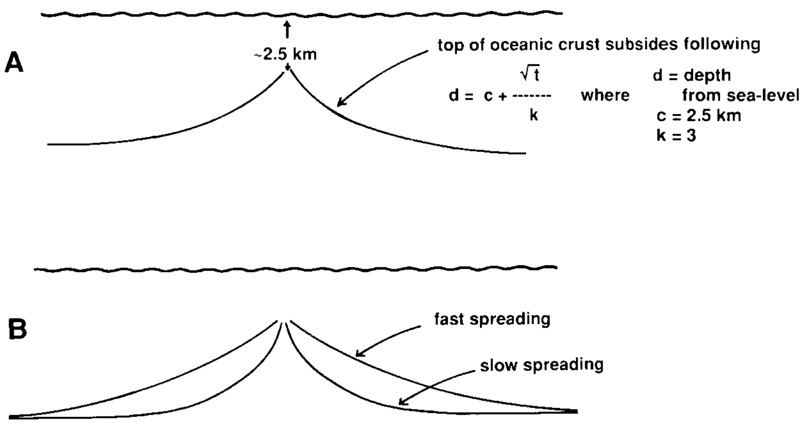

Figure 11: A. Age-dependent cooling and subsidence of ocean floors. B. Difference between slowly spreading and fast-spreading centers. Note that fast-spreading centers create larger ridges and thus diminish the capacity of the ocean basins.

Also, times of major continental collisions are also times of enlarged capacity of ocean basins, because collisional scrunching of continental crust makes its thickness larger but area smaller. Major episodes of continental collisions thus correlate with major regressions.

One of the major driving forces acting on plates is the gravitational pull exerted by major subducted slabs. The longer a subduction zone into which a plate descends, the faster that plate moves. Because collisions eliminate subduction zones, they also effect a slowdown of global plate motion rates. Collisions thus also influence ridge volume and amplify regressions.

Stated simply, a high worldwide sea-level creates a generally warmer and more equable global climate, whereas a low sea-level does the opposite. But a high-sea-level may also increase the rate of CO_2 removal from the atmosphere by depositing more limestone ($CaCO_3$) and thus help its cooling. Because sea-level controls the sculpture of land (by controlling climate and base-level), the distribution and intercommunication of niches, and global climate, it also forms one of the prime controls on the evolution of life.

There is one external agent dependent neither on anything terrestrial nor on solar heat: the extraterrestrial bodies whose orbit cross the earth, and which fall onto it.

Many meteorites of small size (a few cm to a few meters) fall almost daily, but more rarely a major object (with a 10 km or so radius) hits the earth. One such fall some 0.65 billion years ago may have been responsible for poisoning the world ocean and wiping out some 80% of the living species, including the land-living dinosaurs! Such "chance" events with major consequences for the evolution of the earth are reminders that this wonderful planet of ours is indeed a part of an impersonal cosmos in which chance rather than will determines the course of events.

Earth and Thought

In the brief survey presented in this and the precedent chapter, I summarized the very barest outlines of the structure, behavior, and evolution of the earth from its nebular origins some 4.6 billion years ago to the present. It is indeed very remarkable how man, who only about 5000 years ago invented writing as an efficient way of storing and transmitting his knowledge, has managed to learn so much about history that spans such an immense interval of time. This grandiose achievement should not blind us to the fact, however, that was has been told in the above paragraphs is only a good deal of generalization. Almost every part of this story is disputed, and, there are alternative stories that rival the ones I prefer. For instance, I emphasized a homogeneous earth accretion; others prefer an inhomogeneous one. I lean toward an olivine-dominated mantle; others prefer a pyroxene-dominated one. I emphasized a continuous earth evolution dominated by chance events. Others prefer discontinuous story punctuated by deterministic events. I ascribed the major revolutions in the biosphere to the impact of extraterrestrial objects. Others prefer to hold hot-spot volcanism responsible.

Not that these differences of opinion stem from fundamentally different pools of data. The international communication in science and the goodwill and honesty of this unique community of individuals called scientists are such that all earth scientists have more or less the same set of data available to them. The differences are rather the result of how an individual views this common set of data. The sort of ideas brought *in* to explain the data are dependent not so much on the data themselves, but on the individual who considers them, on his or her background, temperament, knowledge, courage, and the like. All these contribute towards building his or her *Leitbilder*, i.e., sets of ideas, beliefs, and convictions that

Figure 12: The erupting volcano (Hasan Dag?) depicted on a wall in a shrine in Çatalhüyük, central Turkey (ca. 6500 BC: Mellaart, 1967). In this earliest known panorama painted by man, the violent volcano may have been considered the terrestrial representative of the male deity of Çatalhüyük, the bull.

generally cannot be rigorously tested. It is in the light of these *Leitbilder* that he or she invents theories or improves them through testing.

The history of the earth sciences, like that of any other science, is a procession of bold conjectures and refutations brought about by observations spurred by the original conjectures. I hold, however, that a number of dramatic manifestations of the dynamism of our planet may have inspired a number of the *Leitbilder* that our forefathers bequeathed to us. Babylonian legends, in which every Great Year (one equinoctial precession cycle) ends with a flood, may represent the memory of regular deglaciations at a time when the precession of the equinoxes had not yet been recognized. This might be the reason why such tremendous, astronomically unacceptable variations are seen in different estimates by the ancients on the duration of a Great Year (from a few thousand to 36,000). A vague periodicity may have impressed itself into the common memory of mankind which may have been compared with the annual, lunar, and diurnal periodicities, implying an orderly behavior of the earth, the heavens, and the female body that was thus deified!

I close this essay with another conjecture: that the earth itself may have inspired the abandonment of the monotheistic "mother goddess" cults, and, with them, the regularist, determinist *Leitbilder*, through the violent activity of a double-peaked volcano in the heart of Asia Minor, the mighty Hasan Dag, which the inhabitants of the first known "city," Çatalhüyük (cf. Mellaart, 1967), seem to have identified with the "unpredictable, disorderly" male deity, the bull. Both the mountain (Fig. 12) and the bull may have been called "Taurus," perhaps inaugurating a new *Leitbild* of irregularity (or maybe resurrecting it from the pre-agricultural hunter's era) marked by smaller catastrophes than "global" floods. This small essay is a modest testimony to the immense distance covered by the thinking of man since those first "earth scientist theories," a distance that has been stamped, however, by a perennial controversy between the two *Leitbilder* of non-uniformist/regularists and the uniformist/ irregularists.

References

Anderson, Don L., "The Earth as a Planet: Paradigms and Paradoxes," *Science*, 223 (1984), pp. 347–355.

Anderson, Don L., "Theory of the *Earth*," Oxford, Blackwell Scientific Publications, 1989.

Broecker, Wallace S., *How to build a Habitable Planet*, Palisades, New York, Eldigio Press, 1985.

Burke, Kevin, and Wilson, J. Turo, "Hot spots on the earth's surface," *Scientific American*, 235 (1976), pp. 46–57.

Condie, Kent C., *Plate Tectonics & Crustal Evolution*, 3rd ed. Oxford, Pergamon Press, 1989.

Cox, Allan, and Hart, Robert Brian, *Plate Tectonics: How it Works*, Oxford, Blackwell Scientific Publications, 1986.

Dewey, John F., "Plate tectonics," *Scientific American*, 226 (1972), pp. 56–57.

Fowler, C.M.R., *The Solid Earth*, Cambridge, Cambridge University Press, 1990.

Gleick, James, *Chaos, Making a New Science*. New York, Viking, 1987.

Gould, Stephen Jay, *Wonderful Life*, New York, W.W. Norton & Company, 1989.

Heezen, Bruce C., and Tharp, Marie, *World Ocean Floor Panorama*, Milwaukee, Mercator Projection, 1977.

Hsü, Kenneth Jinghwa, *The Great Dying*, San Diego, Harcourt Brace Jovanovich, Publishers, 1986.

Jeanloz, Raymond, "The Earth's Core," *Scientific American*, 249 (1983), pp. 40–49

Le Pichon, Xavier, *Leçon Inaugurale*, Collège de France, Chaire de Géodynamique, 1987.

McKenzie, Dan P., "The Earth's Mantle," *Scientific American*, 249 (1983), pp. 50–62.

McKensie, Dan P., and Richter, Frank, "Convection currents in the earth's mantle," *Scientific American*, 235 (1976), pp.72–89.

Mellaart, James, *Çatalhüyük. A Neolithic Town in Anatolia*, London, Thames and Hudson, 1967.

Menard, H. William, *The Ocean of Truth*, Princeton, New Jersey, Princeton University Press, 1986.

Molnar, Peter H., "The Structure of Mountain Ranges," *Scientific American*, 254 (1986), pp.70–79.

Park, R.G., *Geological Structures and Moving Plates*, Glasgow, Blackie, 1988.

Pisias, Nicklas G., and Imbrie, John, "Orbital geometry, CO2 and Pleistocene climate," *Oceanus*, 29 (1986/87), pp. 43–49.

Pitman, W.C., III, and Golovchenko, Xenia, "Quantitative landscape evolution," *Journal of Geophysical Research*, 96 (1991), pp. 6879–6891.

Press, Frank and Siever, Raymond, ed. *Planet Earth*, Reading from *Scientific American*, San Francisco, Freeman and Company, 1974.

Scientific American, *The Dynamic Earth*, special issue, 249 (September 1983).

Skinner, Brian J., and Porter, Stephen C., *Physical Geology*, New York, John Wiley & Sons, 1987.

Smith, David G., ed., *The Cambridge Encyclopaedia of Earth Sciences*. New York, Crown Publishers/Cambridge University Press, 1981.

Uyeda, Seiya, "Recent developments in solid earth sciences," *Journal of Magnetism and Magnetic Materials*, 31–34 (1983), pp. 29–38.

Verhoogen, J., Turner, F.J., Weiss, L.E., Wahrhafting, C., and Fyfe, W.S., *The Earth. An Introduction to Physical Geology*, New York, Holt, Rinehart, and Winston, Inc., 1970.

White, Robert S., and McKenzie, Dan P., "Volcanism at rift," *Scientific American*, 260 (1989), pp.62–71.

Wilson, J. Tuso, ed. *Continents Adrift and Continents Aground*, San Francisco, Freeman & Company, 1976.

Wyllie, Peter, J., *The Dynamic Earth: Textbook in Geosciences*, New York, John Riley & Sons, 1971.

Wyllie, Peter, J., "The Earth's Mantle," *Scientific American*, 232 (1975), pp. 50–63.B.