Lessons for the Earth, Learned from the Planets: The Importance of Place

(Based on a Talk Given to the Geological Society of Finland, November 2007)

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Introduction

In an effort to make sense of the world and to explain its origin, the people of the Earth have devised many creation myths. The great national epic of Finland, the Kalevala (Lönnrot, 1888) begins with the story of the goddess Ilmatar, who descends from the heavens to the sea, where she is tossed about for 700 years. During that time, a duck makes a nest and lays eggs of gold and iron on her knee. When Ilmatar finally moves, the eggs break, and the pieces form the Earth, the starry heavens, the Moon, the Sun, and the cloudy atmosphere.

But transformed, in wondrous beauty
All the fragments come together
Forming pieces two in number,
One the upper, one the lower,
Equal to the one, the other.
From one half the egg, the lower,
Grows the nether vault of Terra:
From the upper half remaining,
Grows the upper vault of Heaven;
From the white part come the moonbeams,
From the yellow part the sunshine,
From the motley part the starlight,
From the dark part grows the cloudage;
And the days speed onward swiftly,
Quickly do the years fly over,
From the shining of the new Sun,
From the lighting of the full Moon.

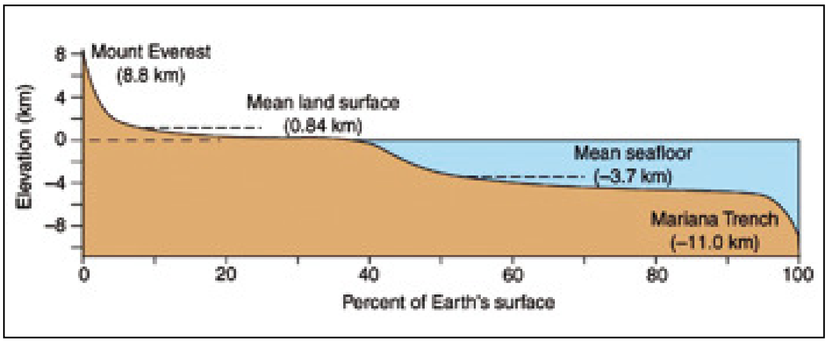
There are, indeed, many creation myths. On the pages that follow, I have attempted to summarize a modern version of such a creation myth, one based on new information we have learned during the last few decades of space exploration. The question I want to address in this essay is, "What lessons about the development of Earth's fundamental features have we learned by studying other planets?" By placing Earth in its planetary context, we may see what is most important and what is only secondary. Perhaps this account will sound just as mythical as Ilmatar or Nut in another hundred years, but let us begin by establishing Earth's distinctive characteristics and then outline a path Earth might have followed to get where it is today.

Planet Earth

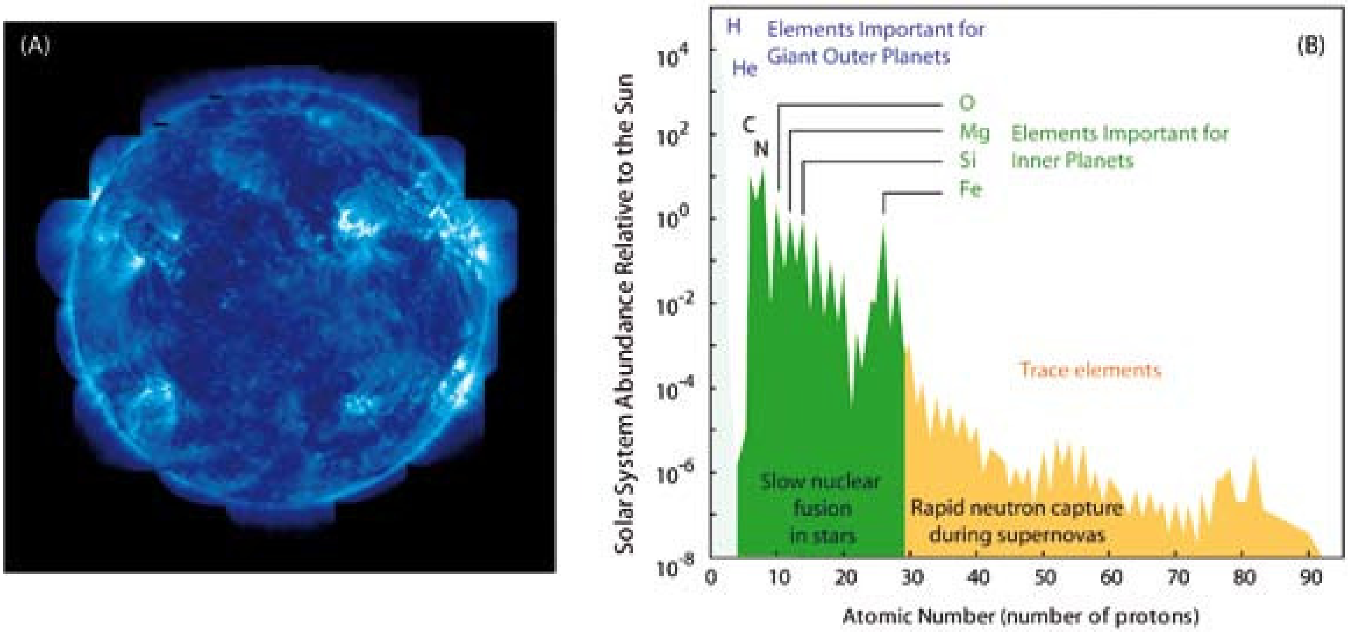
If an alien spacecraft were to enter the inner solar system on some grand quest of planetary discovery, the explorers would be struck by the stark contrast between the Earth and the Moon. They would quickly recognize five fundamental features of planet Earth:

1. High continents;
2. Liquid water;
3. Absence of large impact craters;
4. An oxygen-rich atmosphere; and
5. A discontinuous blanket of greenery.

The continents lie about 4 km above the average ocean floor surface (Figure 1). Earth's high-standing continents reveal that they are made of distinc-



F1. Earth's continents *rise approximately 3 km above the ocean floor as shown on this hypsometric curve for the planet (from Hambin and Christiansen, 2004).*



F2. The Sun, *like other medium-sized stars, generates heavier elements like He from lighter ones like H by the process of nuclear fusion. (A) An ultraviolet image of the Sun taken by the TRACE satellite (TRACE Team, NASA). (B) Element abundance graph and processes of formation.*

tive rocks that have a low density compared to the adjacent ocean basins. The average density of continental crust is about 2.7 Mg/m3, as compared to about 2.9 Mg/m3 for the denser rocks of the oceanic crust (Condie, 2005). The low density of Earth's continents is due in large part to their enrichment in silica and depletion in iron.

Another vital feature of the Earth is its diverse hydrosphere. The existence of water in its three natural states–vapor, liquid, and solid–would reveal even to alien observers that Earth's surface temperature is moderate, not too hot or too cold, but hovering near the triple point of water.

The Moon, like most other planetary bodies, has many meteorite impact craters. The planets and moons of our solar system formed by collisional accretion of debris in orbit around the Sun and most of them retain evidence of at least the final stages of their growth. Earth does not. Plate tectonics, which produces mountain belts, rifted continental margins and midocean ridges, causes Earth's dearth of impact craters. Plate tectonics continually remakes the surface. Old plates of oceanic lithosphere are completely subducted back into the interior and even though the low density continents resist subduction, they are crumpled by collisions that destroy ancient impact craters. Even today, 4.5 billion years after it formed hot and molten, Earth's interior remains hot. Plate tectonics is the surface manifestation of thermal convection. The youthful surface of the planet shows that it is still hot and churning inside. Other impact craters are blanketed by vast sheets of surficial sediment created, in large part, by the action of the hydrosphere. Indeed, the characteristic landform on Earth's continents is the stream valley–a result of the confluence of the two fundamental characteristics noted above–an abundance of liquid water and the presence of high continents.

Even before our hypothetical alien craft came close enough to see these other features, its spectrometers would show that Earth has an atmosphere and a highly unusual one. Unlike other rocky planets, Earth's atmosphere is not dominated by carbon dioxide, but instead consists mostly of nitrogen (N_2) and even more important, it contains about 20% oxygen (O_2). As a result of the abundance of oxygen, Earth also has a radiation shield of ozone.

Finally, on even closer approach to the planet, the exploration party would see that Earth's continents are partially covered by a green blanket whose color and extent shifts with the seasons. This living and breathing cloak of vegetation created the oxygen-rich atmosphere that currently bathes the Earth.

A Seven-Step Cosmological Myth

To understand how this unique set of features formed, let us now consider a history of the Earth divided into seven interdependent steps, leading from the origin of the elements to the generation of silicic continental rocks.

Step 1. Formation of the Elements and Interstellar Nebulas

Planets are made of a great diversity of elements. By and large these diverse elements are relicts of the history of stars. The production of hydrogen and helium harkens back to the Big Bang, which according to the best present estimates occurred about 13.7 billion years ago. All of the other elements on the periodic table, with their diverse sizes, chemical properties, and densities formed subsequently in stars. Step by step fusion properties created the nuclei of heavier elements from lighter ones in vast solar foundries (Figure 2). Medium-sized stars like our Sun are long-lived, but they are only capable of creating the lightest elements–as heavy as carbon which has an atomic number of 6. Once created in the depths of stars, these new elements are delivered back into space during the death throes of the star. Stars like the Sun end their lives by producing some of the galaxy's most beautiful objects–planetary nebulas. The outer layers of the star are ripped off and newly formed elements are recycled back into space where they can be included in a subsequent generation of stars and their planets.

Larger stars can create even heavier elements. By sequential fusion, elements as heavy as iron (atomic number 56) can form inside large stars. Along the path to iron formation, magnesium, oxygen, aluminum, and silicon are also formed by fusion of lighter nuclei. These elements are vital for the formation of rocky planets made of silicates and iron metal. The formation of elements even heavier than iron must await the death of these massive stars. Once iron forms deep inside the core of such a star, the interior becomes unstable as protons and electrons combine to form neutrons and outer layers collapse inward. Chaos accompanies collapse. A huge flux of neutrons bombards existing seed nuclei and creates heavier elements, including important long-lived radioactive elements like uranium and thorium. This rapid cascade of nuclear processes leads to a huge explosion of the star–one type is called a super nova (Figure 3). In 1054 AD, a large, short-lived star exploded to form the Crab nebula, which has been rapidly expanding ever since. But what is most important to our story here is that a vast array of new, heavy elements is blown into space where they eventually cool and condense as interstellar grains of dust or, if they are volatile enough, as gaseous molecules.

Step 2. Nebula Formation and Condensation in a Temperature Gradient

Although we perceive "outer space" to be completely without elemental material, it is not a perfect vacuum. Throughout the galaxy, gases are thinly dispersed. For each 10 cm3 there may be

F3. The Crab nebula (*M1, NGC 1952*) *is a supernova that exploded almost a thousand years ago. It is now about 6 light years across. A supernova like this marks the death of a very large, short-lived star. Such stars generate elements as heavy as Fe by slow fusion processes and then even heavier elements during the explosion itself. As a result, they generate and then expel many elements that will later be used to make new stars with orbiting sets of solid planets. The colors reveal the type and location of some of the most abundant elements expelled by the explosion. Blue represents oxygen in the outer filamentous portion of the nebula, green is sulfur, and red indicates ionized oxygen. A rapidly spinning neutron star, the ultradense remnant of the exploded star, is embedded in the center of the nebula. (NASA/ESA; J. Hester and A. Loll, Arizona State University: STSci-PRC2005-37).*

F4. The Eagle nebula *(M16) is a vast cloud of gas and dust where new stars and planets are forming about 6500 light years away. The huge pillars are 10 light-years high (about twice the distance from our Sun to the next nearest star). A torrent of ultraviolet light from a series of massive, hot, young stars (bright blue stars visible in the inset) has sculpted the details of the pillars. Ghostly streamers of gas boil off the towers. At the top of the tower, thick clouds of hydrogen gas and dust have survived the blast of ultraviolet radiation from the hot, young stars. Inside each of the gaseous pillars, stars may be forming when dense gas collapses under it's own gravitational attraction or where it is rammed together by shock waves moving through the gas. The fingers at the top of the left tower are stellar birthgrounds that are roughly the size of our solar system. The fledgling stars grow as they feed off the surrounding gas cloud until they are separated by "erosion" from their gas supply. The blue color at the top is from glowing oxygen. The red color in the lower region is from glowing hydrogen. (NASA: ESA: STScI: J. Hester and P. Scowen, Arizona State University). Inset: T.A.Rector (University of Alaska Anchorage, NRAO/AUI/NSF and NOAO/AURA/NSF) and B.A.Wolpa (NOAO/AURA/NSF).*

only one atom. (Near Earth's surface, the atmosphere contains about 1020 atoms in the same volume.) The most important of the interstellar gases consist of the most abundant elements–hydrogen, helium, carbon, nitrogen, and oxygen. There are also sparse dust grains composed of metals and silicates. We have seen how the violent deaths of some stars provide a recycling mechanism to charge interstellar space with these materials. Locally, these elements re-accumulate to form gigantic molecular clouds–large concentrations of gas and dust, which may have approximately 1,000 atoms/cm3. Such dense, dusty clouds are called nebulas (Figure 4) and have been detected in several places in the galaxy.

These misty nebulas are the birth grounds of the next generation of stars. Gravitational attraction and contraction can occur when the density of the gas is as low as 20 atoms cm^3. The gravitational collapse of a nebular cloud may be fairly rapid. Small density differences and gas turbulence can produce several subregions from a large nebula. Each concentration may eventually collapse independently and become a star. Open star clusters and some multiple star systems are thought to result from the fragmentation of contracting nebulas.

The contraction of the cloud of gas and dust guarantees more collisions among the atoms within it, producing heat. Some of this heat is dissipated by infrared radiation into space; the rest is retained and elevates the temperature of the nebula. Because the interior of the nebula gradually warms, increased gas pressure causes the collapse of the cloud to slow down. When temperatures exceed about 10,000 K a protostar near the center of the nebula may begin to radiate light produced by the release of this energy (nuclear reactions begin at a later stage). As a result, the inner portions of the nebula become much warmer than its outer reaches.

During this early contraction, the gas cloud begins to rotate faster and faster, like a figure skater who draws in her arms during a spin. A flattened disk of material with stable orbits forms in the equatorial plane of protostar. Planets eventually form in this disk. In fact, disks of dust have been discovered around young nearby stars (Figure 5). Rapid and irregular outbursts of light and strong magnetic fields are associated with the next stage of slow gravitational contraction. During this so-called T-Tauri phase, large amounts of matter are ejected from the nebula in a type of "wind" that sweeps much of the uncondensed gas and even some light dust from the inner part of the evolving nebular disk.

As the star continues to contract, critical temperatures (around 8,000,000 K) and pressures are reached at which thermonuclear fusion of hydrogen starts. When the nuclear fires are ignited, the temperature rises farther and essentially halts further contraction of the star. Stars the size of the Sun may maintain this near equilibrium state for billions of years, as they gradually consume their budget of hydrogen to form helium. The evolution from stellar nebula to hydrogen-burning star may only take 100,000 years---a short part of the solar system's 4.5-billion-year history (Table 1).

Now let us go back a short time in this grand scenario and try to construct a plausible scheme for the development of the planets in our solar system. Near the Sun, most of the material in the nebular disk was vaporized and solids probably started to form as the protostar contracted and the surrounding nebula began to cool. The types of solids

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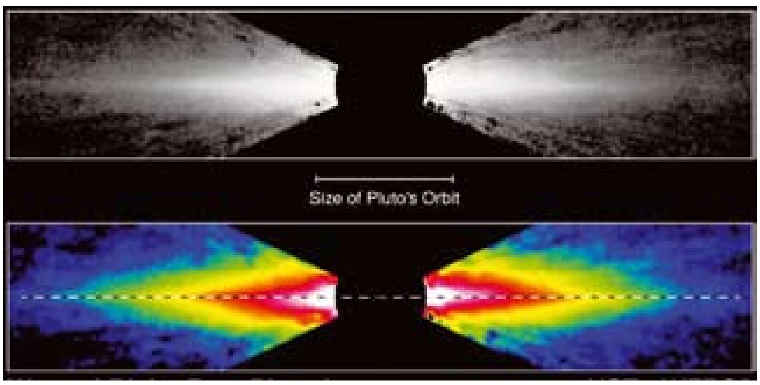
Table 1. Key events in evolution of the Earth

Date (Ma)	Duration (Ma)	Event
4,600	0.1	Nebula to star
4,567	5	Condensation and disk formation
4,565-4,535	30	Accretion
4,565-4535	30	Differentiation
4,537		Giant impact
4,400-4,000		Oceans form by condensation
4,400-3,800		Life begins
3,900-3,800		Last major impacts
4,000-3,800		Oldest continental remnants preserved
3,800		Archean starts
3,000-2,000		Continental growth accelerates
2,500-2,000		Atmosphere becomes O_2-rich
3,000-2,500		Modern subduction starts
3,000-2,500		Sodic granitoids give way to potassic granites
2,500		Proterozoic starts
		Modern subduction starts
540		Phanerozoic starts
-5,000		Sun becomes a red giant

Dates summarized from Rossing et al. (2007) and Rollinson (2007)

that were stable depended on the chemical composition and temperature of the nebula. Most planetary scientists assume that the composition of the nebular disk was about the same as that of the present-day Sun. Regarding temperature, there is some evidence in the primitive class of meteorites called carbonaceous chondrites that temperatures approaching 1800 K existed near the forming star; temperatures dropped to very low values (30 K) in the outer part of the nebula. Using these assumptions regarding composition and temperatures and another for pressure within the disk, we can calculate the sequence and composition of the solids condensing from the cooling gas. Table 2 shows the generalized results of such calculations.

The solids that condensed near the Sun were probably small quantities of highly refractory elements such as tungsten, osmium, and zirconium. At lower temperatures (about 1700 K) significant amounts calcium and aluminum oxides crystallized. Grains of metallic iron-nickel precipitated directly from the gas at about 1470 K. Where temperatures in the nebula were lower than about 1450 K, the oxide minerals reacted with the gas to form silicate minerals such as Mg-rich olivine and pyroxene. Alkali-bearing silicates condensed at about 1000 K, forming feldspars. At about 700 K, previously condensed metallic iron reacted with sulfur in the gas to form troilite (FeS), an important mineral in some meteorites. At lower temperatures,



F5. Beta Pictoris *is a young star that is still surrounded by a disk of debris as revealed by this Hubble Space telescope image. The different colors represent the amount of dust in orbit around the star. The disk extends far from the star. (C. Burrows and J. Krist STSci).*

Table 2. Condensation temperatures from the solar nebula

Phase	°K
Tungsten and zirconium	2000-1800
Ca, Al, Ti oxides	1900-1550
Metallic Fe-Ni	1500-1300
Forsterite and enstatite	1440-1300
Ca-plagioclase	1370-1170
Na-K-feldspars	1000-800
Troilite (FeS)	700-660
Fe oxides	470-370
Carbonaceous compounds	470-370
Hydrated Mg silicates	370-270
Water ice	180
Ammonia·H_2O ice	120
Methane and clathrate	40

Data from K. Lodders (2003)

Assumes a pressure of 10^{-4} atm

iron-rich olivine and oxides like magnetite crystallized as solids. Where temperatures in the nebula were about 400 K, sulfates, carbonates, and hydrated silicates formed by reaction of early formed minerals with the gas.

Even farther from the proto-Sun, the nebula was cooler than 300 K and sticky carbonaceous compounds precipitated. Where the temperature in the nebula reached about 185 K water ice formed, probably in a blizzard of snowflakes. At even lower temperatures and even farther from the Sun, volatile substances such as ammonia (NH_3), methane (CH_4), and nitrogen (N_2) which we normally regard to be gases, crystallized as icy solids. Because the constituent elements of these volatile compounds were much more abundant than the refractory elements (Figure 2), the condensation process quite literally snowballed where the ices were stable. Some volatile compounds, like hydrogen (H_2) and helium (He) never condensed to form solids, even in the cold outer reaches of the nebula. At these low temperatures, the nebula consisted of a mixture of carbonaceous materials, hydrated silicates, sulfates, ices (of water, methane, and ammonia) and uncondensed gases---mostly hydrogen and helium. Realizing that the silicate component of the condensed materials would only be a small proportion of the nebular mass, a condensate formed in the coldest regions of the nebula would be little more than a dirty snowball.

This theoretical model, even if it is simple, explains many of the gross compositional features of the planets. It predicts that the planets that formed near the Sun would be relatively small, rich in silicates and iron, and consequently dense. Significantly, it predicts that hydrous silicates should have condensed near Earth's present position and beyond. In addition, this condensation model posits that the outer planets should be large, ice-rich planets, which, because of the mass of early formed ice acquired thick atmospheres of gravitationally trapped remnants of the nebula. The most obvious compositional differences between the inner and outer planets can be explained by this sort of model of nebular condensation.

The reasons for the size differences between the inner and the outer planets are suggested by the bulk composition of the nebula itself. Even if the entire refractory or rocky component condensed, it would represent less than 0.5 percent of the total mass available in a nebula of solar composition (Figure 2). Since all of the inner planets are predominantly rocky, more than 99.5 percent of their potential mass is missing---it must have been too volatile to condense in the warm inner region of the developing solar system. The outer planets (Jupiter, Saturn, Uranus, Neptune, as well as their satellites and objects in the Kuiper belt) formed from material that condensed at low temperatures (about 200 to 30 K), where ices of water, ammonia and methane could form in addition to the rocky component. These ices probably accounted for a much greater mass of the nebula–about 1.5 percent. Substantial portions of the outer planets, especially of Uranus and Neptune, are postulated to consist of the abundant elements that make these ices.

Table 3. Key events in the evolution of life on Earth

Date (Ma)	Event	Notes
	Monomers, polymers, RNA, DNA, cells	
4,000	Life originates	
3,800	Autotrophs probably evolved	
3,500	Prokaryotes	Cyanobacteria, stromatolites, microbial and unicellular
		Produced O_2
2,300	Eukaryotes	Fossils as old as 1,900 Ma
		Required O_2
600	Simple animals	
550	Exoskeltons on animals	Cambrian "explosion"
530	Vertebrate animals	
470	Land plants	
410	Vascular plants	
370	Amphibians	
330	Reptiles	
310	Insects	
215	Mammals	
210	Flowering plants	
4	Australopithecus	

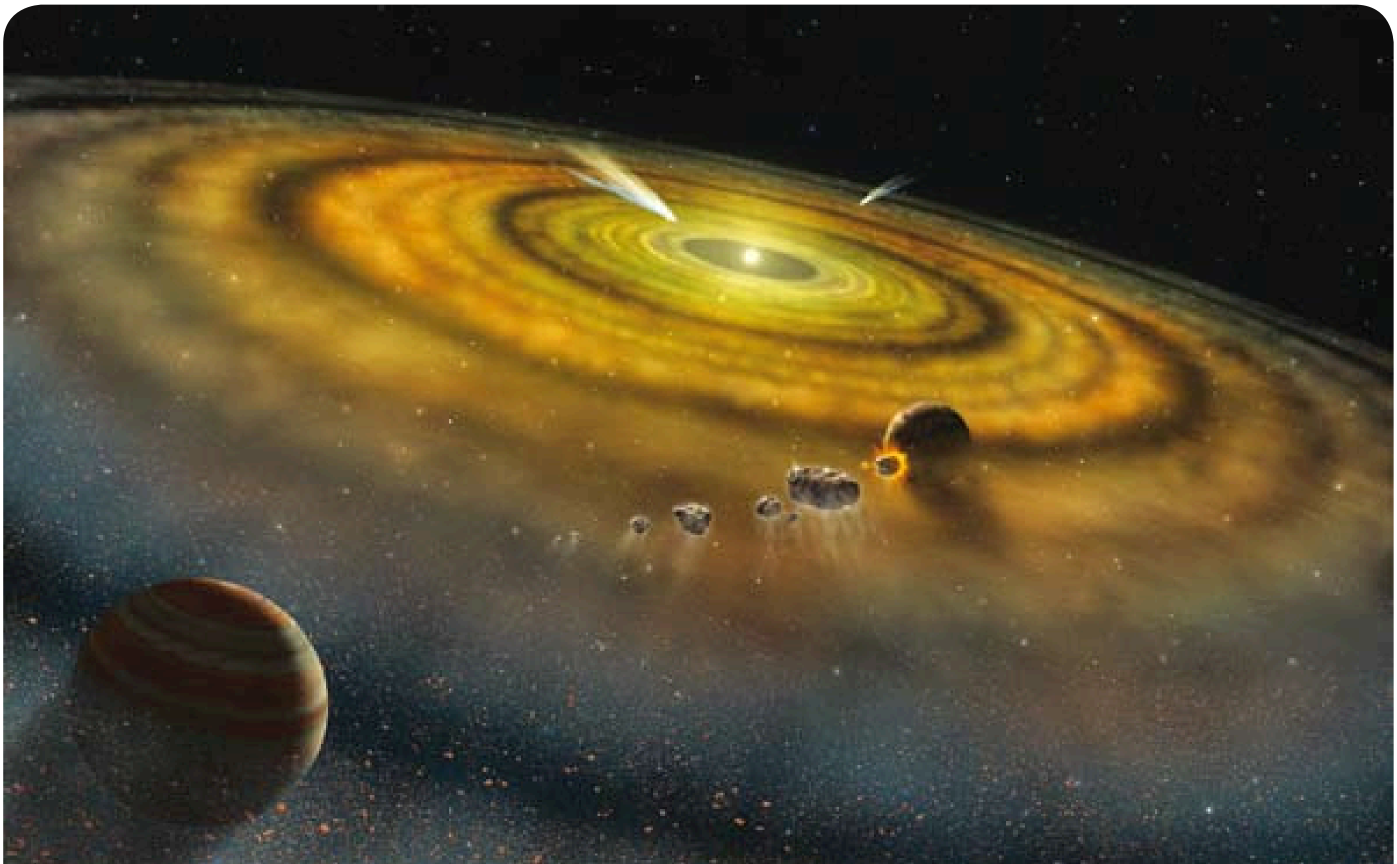
Of what importance was condensation in a thermal gradient to biological processes on the Earth? Because of the thermal gradient, the materials that formed the Earth included just the right mix of elements. For example, it was far enough from the Sun that they included just the right proportions of hydrous silicates from which our oceans eventually formed, but not so much that the planet was perpetually enveloped by a deep global ocean. The planet ended up with sufficient volatile carbon to form organic molecules, but not so much that the water was consumed by reacting with carbon to form a reduced, methane-rich atmosphere. Even today, this thermal gradient exists and is extremely important for Earth's history. If Earth were 5% closer to the Sun, it may have been too warm for liquid water to have ever precipitated. If the planet were 5% farther away, Earth's surface water may have frozen into a glacial state. In short, the nebular disk around the Sun possessed a strong thermal gradient that was, and still is, very important in planetary evolution.

Step 3. Accretion

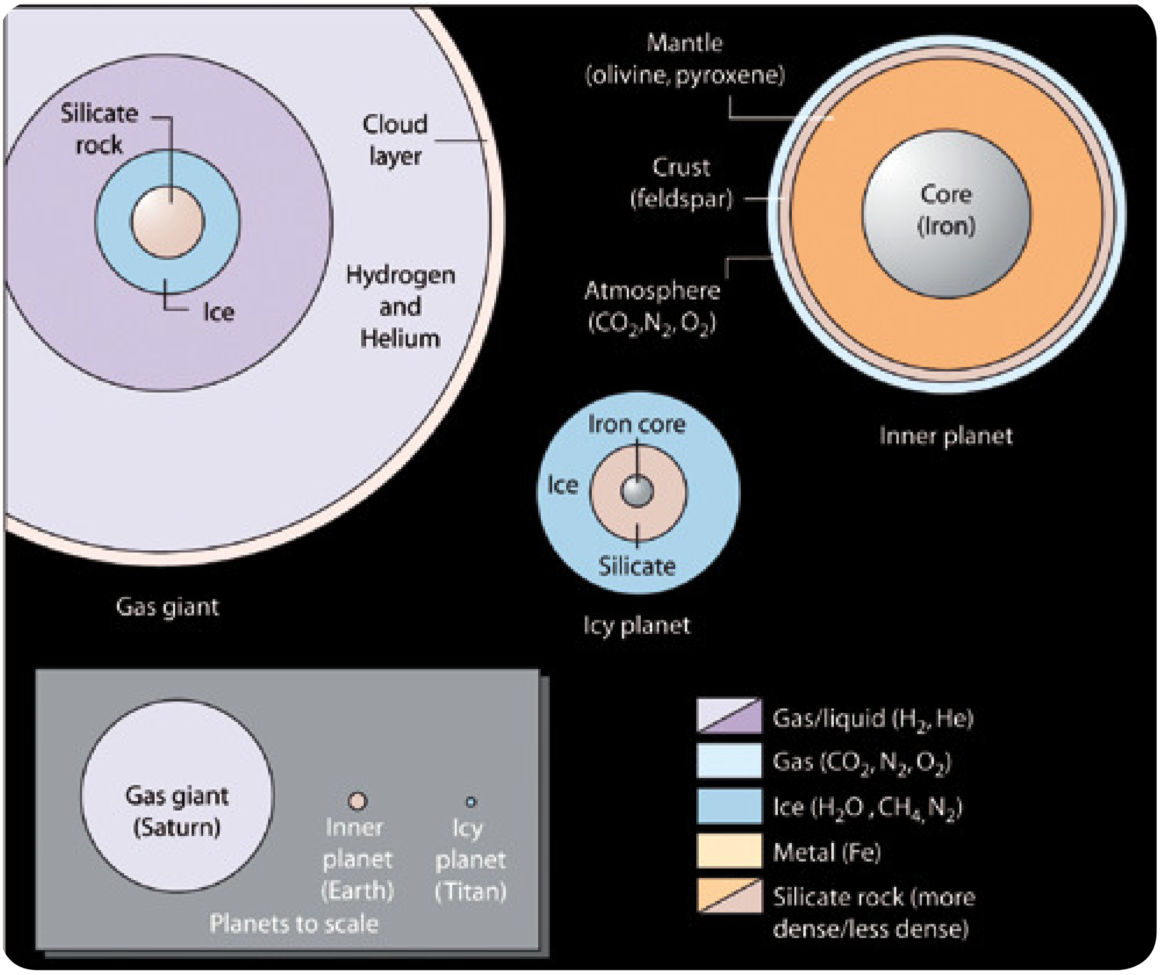
Condensation in a temperature gradient may account for the chemical composition of the planets, but it is unlikely that the planets simply crystallized grain by grain and layer by layer from a dusty nebula. What probably happened was more complex. Once the orbits of the condensing grains had settled into the central plane of the nebula, it appears that planetesimals with diameters of a few kilometers formed. Some scientists suggest that this was accomplished by gravitational grain-by-grain accretion to produce streams or clusters of small bodies that moved in nearly coincident circular orbits. Collisions within or between planetesimal swarms eventually led to the accumulation (not destruction) of even larger planetesimals. Some of these planets in embryo were probably as large as the Moon or even Mars, but collisions also produced small fragments that were later accreted. Some impact events may have resulted in total disruption of a body, followed by its reaccretion. For a given distance from the Sun, one body eventually became gravitationally dominant and swept up most of the material near its orbit. This process of accumulation of the planets from smaller bodies is called collisional accretion and was probably complete within a few million years. Some terrestrial planets, especially the Moon and Mercury, retain dramatic evidence of the last phase of accretion. Their intensely cratered surfaces were produced by the last infalls of material that lingered in their paths even after they had assumed solid spherical shapes. In short, the elemental material of our solar system evolved from gas to dust to clots in co-orbiting streams that eventually accreted to form planets (Figure 6).

Jupiter (and the other outer planets) grew larger than the inner planets because of the abundance of icy condensates in the cooler outer nebula. Small

Table 4. Checklist of some requirements for the development of continents					
Planet	Large Size	Volatiles	Atmosphere	Temperature	Liquid Water
Mercury					
Venus	x		x		
Earth	x	x	x	x	x
The Moon					
Mars		x	x	o	x
Asteroids					
Jupiter			x		
Io					
Europa		x			x
Ganymede		x			
Callisto		x			
Other moons		x			
Saturn			x		
Titan		x	x		
Other moons		x			
Uranus			x		
Moons		x			
Nepture			x		
Moons		x			
Kuiper Belt Objects					
Notes					
Large size	75% of Earth diameter				



F6. Collisional accretion *of small particles that condensed from the solar nebula is depicted in this artist's conception of a young star with a disk of debris orbiting around it. Near the star, the temperature is high and only metals and silicates are stable. Small, dense planets like the Earth can form in this region. Farther from the star, ice is abundant and larger planets have formed, which have captured large amounts of nebular gas to make thick, banded atmospheres. The tails of two icy comets following highly inclined orbits are shown in the inner solar system. (NASA/FUSE/Lynette Cook).*



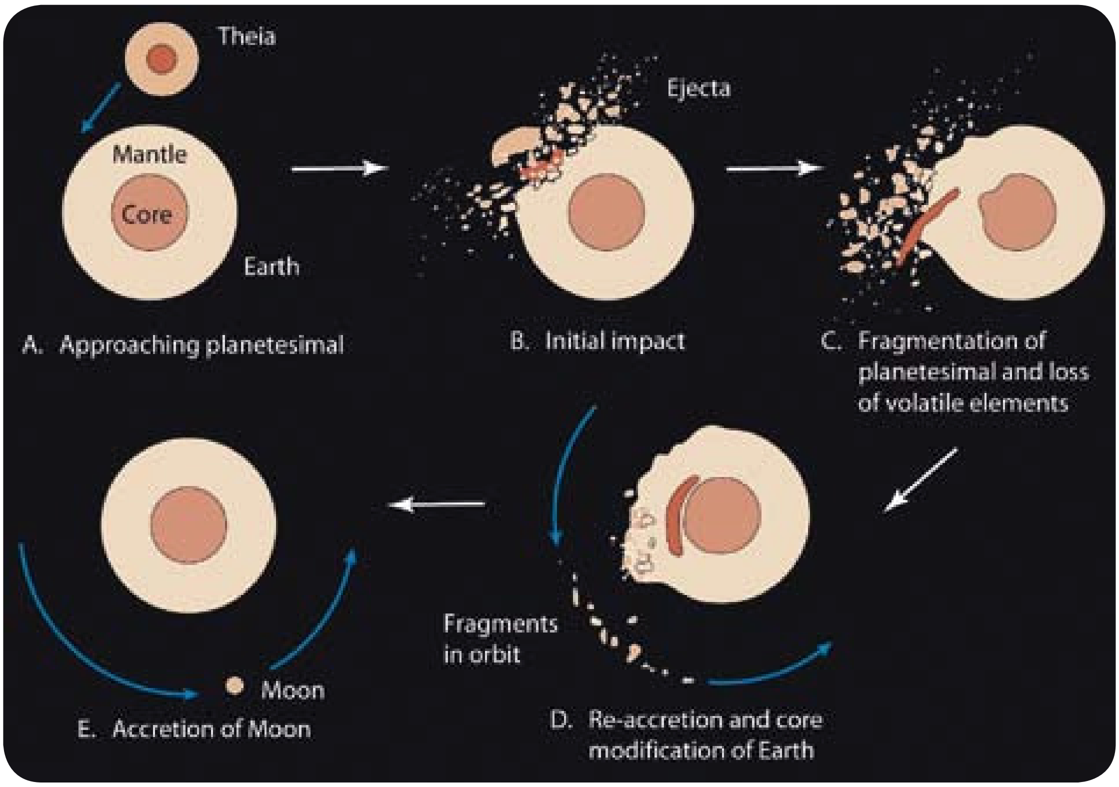
F7. Three different types of "planets" *are found in the solar system as shown in these simplified cross sections. The inner planets are small and made mostly of silicates and iron metal. The outer planets are large and made largely of hydrogen and heliu. The icy dwarf planets and satellites of the outer solar system are small and have surfaces dominted by water ice. An example of each is drawn to scale in the lower left inset. (modified from Hamblin and Christiansen, 2004).*

nebular disks also formed around the larger planets. As these miniature nebulas were probably very similar to the larger solar nebula, condensation and collisional accretion produced large systems of natural satellites that encircle Jupiter, Saturn, Uranus and Neptune. Simultaneously, large quantities of the uncondensable nebular gases surrounding the growing icy planets became hydrodynamically unstable and collapsed onto the planets' icy cores to form thick, colorful atmospheres. In contrast, the present atmospheres of Venus, Earth, and Mars are largely secondary and were most likely expelled from the interiors of their respective planets rather than inherited from the nebula.

After condensation and accretion, a myriad of planets and their moons circled the Sun. These planetary bodies can be divided into three distinctive compositional types–dense rocky inner planets and the smaller asteroids, large H-He rich outer planets, and a set of dwarf planets and planetary satellites in the cold outer part of the solar system with large proportions of ice (Figure 7).

Focusing for the moment on the importance of these events for Earth's later history, we must note that Earth probably had a very dramatic accretion history (Figure 8). It is likely that Earth collided with a Mars-sized planetesimal and in the process ejected debris which accreted in Earth orbit to form the Moon. This giant impact would have ejected any atmosphere that had formed, boiled away any liquid water that had accumulated on the surface, and probably melted the outer part of the planet to a depth of several hundreds of kilometers (Taylor and McLennan, 2005).

Another element of the accretion history that is important to a planet's subsequent history is the simplest of all its features–its size. The size of a planet influences how rapidly it loses the heat released from its interior. All the heat generated within a planetary body must eventually be transported to the surface by conduction or convection and then radiated away. Thus, small planets with large surface area to mass ratios cool faster as heat is readily radiated away into space. Large planets lose their heat much more slowly (Figure 9). Earth accreted in just the right part of the solar system to become fairly large (about 12,800 km in diameter)--large enough that its cooling has been very slow.



F8. A giant collision *of Theia (a hypothetical body the size of Mars named for the mother of Selene the moon goddess) with the early Earth may have ejected material into orbit, where it accreted to form the Moon. The iron core of Theia would have plunged through Earth's mantle and merged with Earth's. Earth may have been stripped of its primordial atmosphere and a thick ocean of magma may have formed from the heat released during impact. (Modified from Hamblin and Christiansen, 2004).*

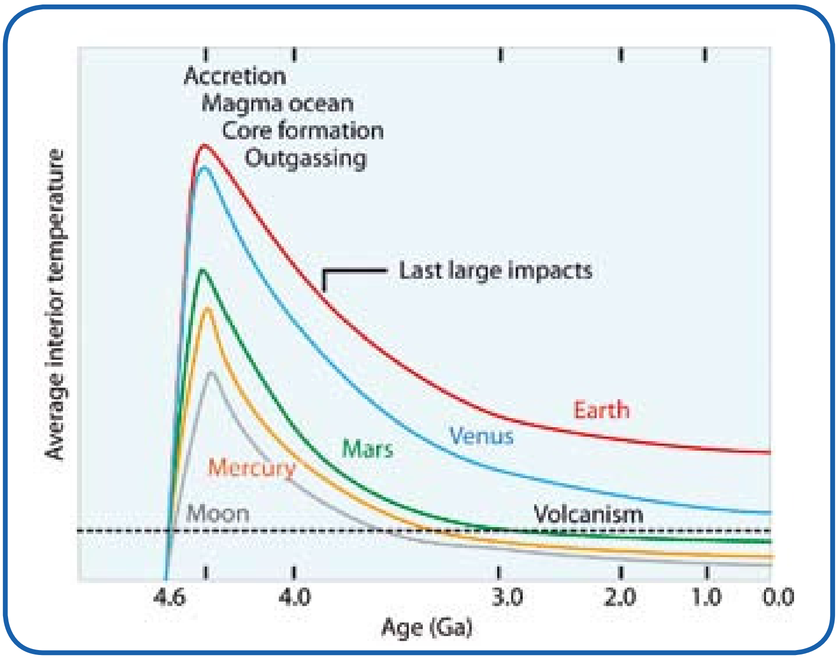
Even though 4.5 billion years have passed since it formed, Earth's temperature is still above the melting point of silicate rocks in small portions of its mantle and above the melting temperature of iron through much of its deep interior. Because of its high internal temperature, Earth's lithosphere is still relatively thin–less than a few hundred kilometers thick in most places–and able to move across the surface. For the evolution of large thick continents, it may have been important that the planet remained warm for a long time so that plate tectonics persisted into the biological era. Again, Earth formed in just the right place.

Step 4. Internal Differentiation of the Planets and Origin of the Lithosphere

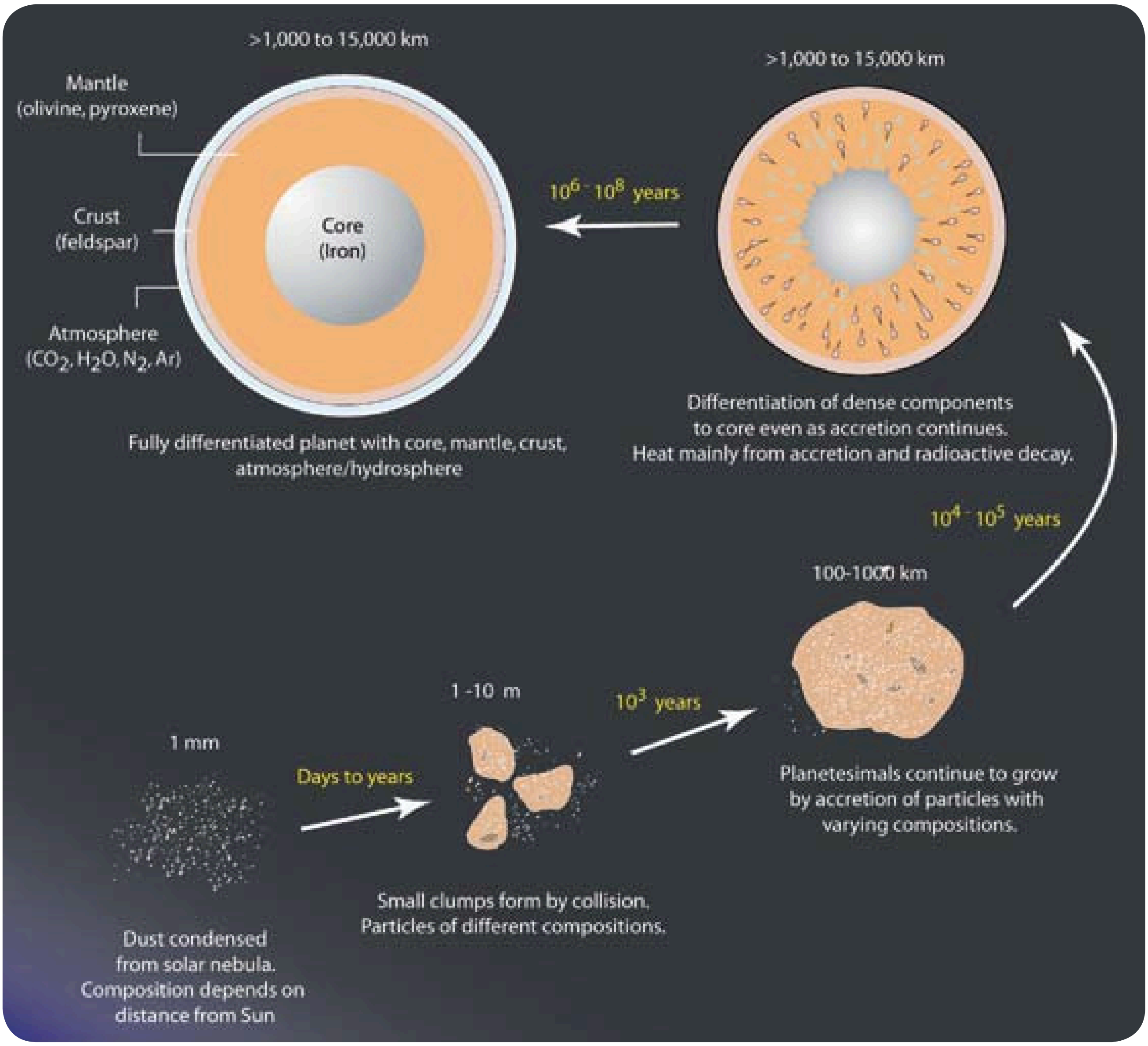
Accretion was accompanied by the internal differentiation of the planets. This produced a variety of layered internal structures, depending on variables such as size, density, and composition of the planetary body (Figure 10). Differentiation within planets occurs because elements have distinctive physical properties (mostly density) and chemical affinities, which allow them to separate from one another. For example, a large group of elements has an affinity to metallic iron. These metals include relatively dense elements such as iron, nickel, and cobalt. Other geochemical groups have affinities for oxygen and silicon and form rocky silicate minerals. These elements include aluminum, calcium, sodium, and potassium; they form minerals that are less dense than metallic iron. Ices form low density solids only at low temperature. Of course, the most abundant is water (H_2O), but methane (CH_4) and nitrogen (N_2) are other important ices. Some elements, like hydrogen, helium, neon, carbon, and oxygen, combine to form various low density gases that accumulate in the atmosphere of a planet. These are the atmophile elements. Several elements fall in more than one group, depending on external conditions.

Distinctive features of the metals include their high densities and high conductivities of heat and electricity. Apparently, metals have accumulated in the cores of several planets by gravitational sinking. Convection in a molten core of metal probably produces the magnetic field that envelopes the Earth. If the planets were originally homogeneous, core formation required considerable redistribution of elements. This mobility of planetary materials may seem at odds with our experience with the "solid" Earth, but under high temperature and pressure rocks become weak and behave much like fluids (even when they are not molten). This plasticity allows the transport of materials during planetary differentiation, but is largely dependent on a critical temperature within the planet. Therefore, planetary differentiation is intimately tied to the thermal history of a planet.

The most important heat source for the differentiation of the planets may have been accretionary heating. Short-lived radioactive isotopes of aluminum and iron may have substantially heated small planetesimals, but it seems unlikely that these ele-



F9. Thermal evolution *of a planet is marked by an early increase in temperature related to heating by accretion and enhanced radiogenic heat followed by a long slow cooling period. Large planets reach higher temperatures and cool slower than smaller planets. The dashed line shows a hypothetical threshold below which the temperature in the planet does not allow volcanism to occur. (Modified from Condie, 2005).*



F10. The planets formed *by condensation of solid grains from the solar nebula, followed by accretion to make larger particles and planetesimals, and finally differentiation–if the planetary body is large enough. This schematic diagram emphasizes the evolution of terrestrial planets.*

ments persisted much past the planetesimal stage. Likewise, electromagnetic heating associated with a T-Tauri phase probably occurred before the planets accreted. Long-lived radioactivity, although important in sustaining the differentiation and subsequent geologic activity of the planets, probably contributed as little as 300 K to the temperature of the primitive undifferentiated planets. In contrast, thousands of degrees of heat may have been generated by collisional accretion. It is estimated that the average temperature of Earth would have been about 30,000 K if all of this heat had been retained (1300 K for the Moon, 4000 K for Mercury, 6000 K for Mars, and 25,000 K for Venus). Of course, much of this heat was quickly radiated away into space, but since iron- and magnesium-rich silicates melt at temperatures of about 1400 K and ices melt at temperatures below 300 K, retention of even a small fraction of the accretionary heat could lead to melting or even vaporization of planetary materials. Once initiated by accretionary heating, the process of differentiation may have been invigorated by core formation as gravitational potential was converted to thermal energy.

When Earth differentiated, a metallic core and mantle made of dense Fe-Mg rich silicates formed. When the mantle melted, either as a result of large impacts or from heat released by radioactive decay, low density magma rose to the surface and accumulated to form the feldspar-rich crust, Earth's outermost layer. Experimental petrology tells us that basaltic magma would be produced by partially melting of the mantle, but we have no scraps of Earth's original crust to verify that assumption. The earliest crust must have formed by extrusion of basaltic lava and grown within by intrusion. Vast floods of basaltic lava or large shield volcanoes may have dominated Earth's Hadean landscape, just as they do on Venus today. Earth's earliest crust formed by the extraction of basaltic magma from the mantle.

Differentiation of Earth's metallic core must have occurred under conditions that did not consume all of its water. If metallic iron comes in contact with water, it will react to form hydrogen gas and iron oxide, destroying the water (Hemley and Mao, 2002). Hydrogen could have combined with the metal and sunk to the core or it could have formed hydrogen gas and seeped to the surface and then escaped to space. Either scenario would leave Earth a water-poor planet. This is what could have happened, for some reason it did not.

Step 5. Origin and Evolution of the Atmosphere and Hydrosphere

As this basaltic magma was formed in the hot mantle, significant quantities of H_2O and CO_2 were also removed from volatile-bearing minerals in the mantle and transferred to the buoyant magmas. Other volatiles must have outgassed as well including N_2, Ar, H_2S, and CH_4. As the magmas erupted, these volatiles were released to form the atmosphere. Initially, when the early Earth was still hot, the volatiles probably stayed as gases in the atmosphere, but as Earth cooled, water precipitated as rain and snow and fell onto the surface. Eventually, and probably very early, oceans of water accumulated and filled and eroded the impact craters that were still forming at the time. Fractures and pores in the crust were filled with groundwater. Ice caps and glaciers may have formed in high mountain ranges or at the poles.

According to this scenario Earth's atmosphere is secondary, formed by release from the planet's interior. It is not a primary atmosphere inherited from the solar nebula, which would have been made of

F11. Stromatolites *like these at Lake Thetis, Western Australia, form from mats of cyanobacteria. Some of the oldest fossils known are very similar to these modern versions. These organisms use photosynthesis to extract CO_2 from the atmosphere and release O_2 in the process. (Photograph by Ruth Ellison)* hydrogen and helium. Earth may have lost an earlier endowment of volatiles as a result of the T-Tauri phase or an early atmosphere may have been stripped away by the giant Moon-forming impact, but it was subsequently re-generated from within.

Liquid water must have precipitated by at least 4 Ga (e.g., Wilde et al., 2001). Some of Earth's earliest rocks were deposited as fluvial sediments. The early ocean was lifeless and anoxic; the atmosphere was probably dominated by CO_2 and with a much higher pressure than today's 1 bar. Some estimates place the atmospheric pressure at 50 b or more. Once liquid water precipitated, dissolved carbonate ions formed by equilibration with the CO_2-rich atmosphere. As rain and seawater interacted with the basaltic crust, Ca^{2+} ions were released to hydrothermal fluids or by weathering of feldspars and pyroxenes to rivers. Both sources eventually released these ions to the ocean where they reacted to make solid carbonate minerals. As these inorganic reactions proceeded, the carbon dioxide content of the atmosphere was reduced, even while more was released by volcanism.

Step 6. Origin of the Biosphere

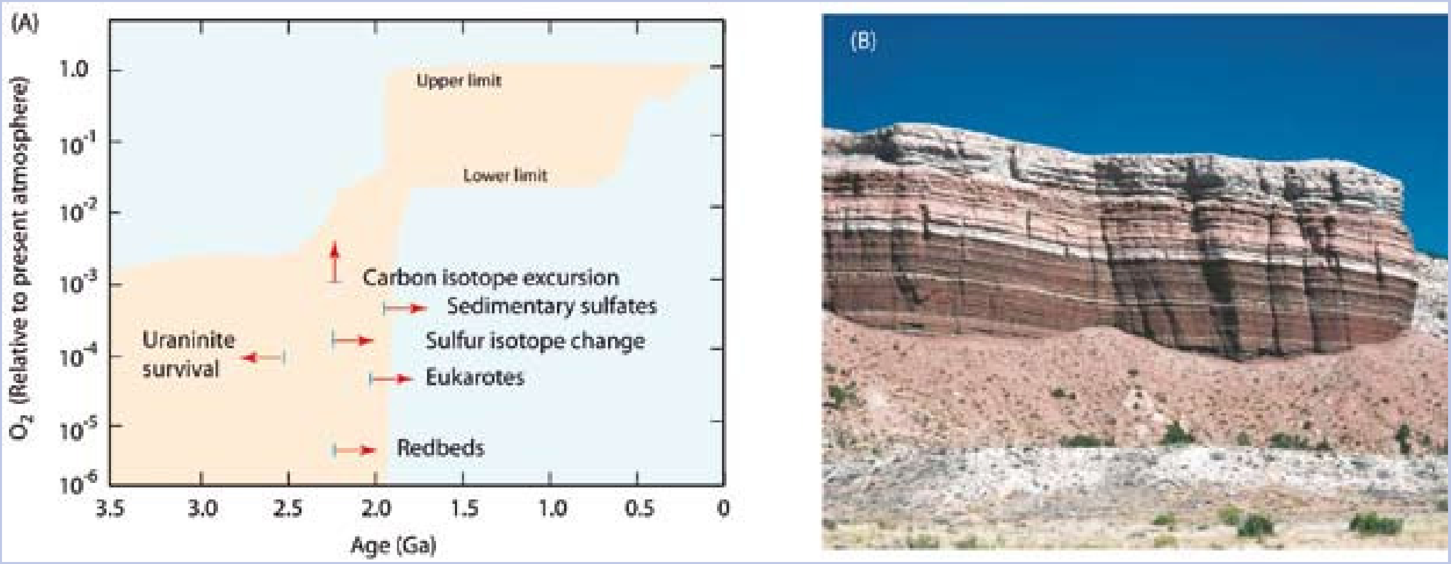
The climactic phase of Earth's evolution may have been the origin of self-replicating molecules–life (Table 3). Geochemical tracers and meager fossil remains show that life evolved early on Earth. For the purposes of this essay, it is important to understand some of the basic requirements for life. They include the presence of liquid water, a moderate temperature, and an energy source. Water is essential for life as we know it. As a liquid, it has a very low viscosity and flows readily; the polar character of water molecules makes it a good solvent and ions can diffuse readily or be advected by flow. Thus, it can serve as the medium through which nutrients and wastes must flow. Temperature is also critical, if for no other reason than to stabilize liquid water. An energy source is needed to help break chemical bonds and create new complex molecules and to drive metabolic reactions. Currently, both solar energy and geothermal energy are considered as likely sources of thermal energy.

Cyanobacteria apparently originated by about 3.5 Ga (Figure 11). The oldest fossils are similar to modern prokaryotes–aquatic bacteria that obtain energy through photosynthesis and produce O2 as a byproduct. Stromatolitic mats of cyanobacteria marked Earth's ancient shallow seas. One of their many effects on the larger Earth system was the progressive oxidation of the atmosphere. Even as carbon dioxide abundances were in decline, cyanobacteria began to release free oxygen. Initially, much of the oxygen must have been consumed by reactions with other materials. However, a wide variety of geologic evidence shows free oxygen began to accumulate in the atmosphere by about 2.5 to 2.0 Ga (Condie, 2005). Eucaryotes appeared on the scene about this time. Significantly, although O_2 is a poison to many prokaryotes, it is a requirement for eucaryotes. Apparently, cyanobacteria had so modified their environment that other species arose that could survive and thrive in the new conditions. Some of the most dramatic evidences of this atmospheric transition are the vast sedimentary deposits of banded iron formations that accumulated in the shallow oceans. In its reduced Fe^{2+} state, dissolved iron is fairly soluble, but when oxidized to Fe^{3+}, little iron can be carried in solution. Earth's oceans, once "filled" with dissolved Fe^{2+}, rusted. Sedimentary deposits of sulfate–the form of sulfur stable in an oxygen-rich atmosphere--appear on the continents about this same time, as do fluvial redbeds. As a result of the evolution of the life, the release of O_2, and this progressive oxidation, Earth became a red planet. As life continued to evolve into more and more complex forms, the proportion of O_2 in the atmosphere continued to climb to near modern levels (about 20% O_2) about 2.0 to 0.5 Ga (Figure 12).

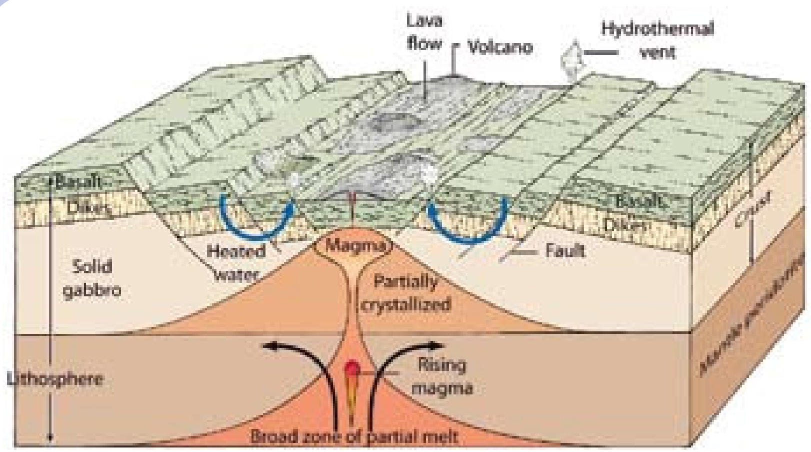
Step 7. Seafloor Spreading, Seas, Subduction, and Silicic Magma

Another important series of events was taking place simultaneously. Sometime during the first few billion years of Earth history, subduction of oceanic lithosphere began (e.g., Smithies et al., 2007). Exactly when subduction started is debated, but much evidence suggests that it began in the Archean and was well established by the Proterozoic. The subduction of oceanic lithosphere requires spreading and the creation of new oceanic lithosphere from hot up-welling mantle at midocean ridges. Decompression melting creates basaltic magma from which the oceanic crust is constructed by volcanic eruption and intrusion (Figure 13).

Newly formed hot crust is immersed in seawater which infiltrates to depths of several kilometers, locally penetrating into the mantle. Along its flow path, the water becomes heated and reacts chemically with the crust to create a seafloor hydrothermal system. A host of new minerals is stabilized in the process. The hot seawater destroys primary igneous minerals (olivine, pyroxene, Ca-plagioclase) and replaces them with clay, zeolites, and iron oxides. The rocks of the lithosphere change in two



F12. The oxygen content *of Earth's atmosphere has grown with time. (A) Several kinds of evidence show that atmospheric O_2 has increased with time. The Archean atmosphere lacked oxygen (modified from Condie, 2005). (B) Sedimentary rocks with oxidized iron and thin layers of gypsum with oxidized sulfur are common in Phanerozoic rocks like these from southern Utah but they are not found in Earth's oldest rocks. (Photograph by W.K. Hamblin)*



F13. Midocean ridges *form where two plates of oceanic lithosphere separate. Decompression of rising mantle beneath the ridge creates basaltic magma that accumulates as lava and intrusions to form the ocean crust. Recharge of mafic magma and tholeiitic differentiation trends minimize the amount of silicic magma generated at midocean ridges. Seawater flows through the hot rocks at the ridges and hydrates and oxidizes the crust. (Modified from Hamblin and Christiansen, 2004)*

very important ways–they become hydrated and oxidized (Figure 14).

As a result of seafloor spreading, eventually the wet oxidized lithosphere reaches a subduction zone and the slab dives into the hot mantle below. This triggers another series of reactions which lead to the production of magma so evident in the explosive stratovolcanoes that mark many subduction zones. The prevailing hypothesis for the origin of subduction magmas holds that as the plate subducts and heats up it dehydrates. The hydrous minerals formed at the ocean ridge eventually break down to form anhydrous minerals and an aqueous fluid. This occurs at depths of about 100 km or so (Figure 15). Because it was released from oxidized rock, the fluid is also oxidized–especially when compared to the overlying mantle wedge. When aqueous fluid rises buoyantly into the overlying mantle, the melting point of the mantle is lowered and partial melting ensues. The partial melt mixes with the slab-derived fluid (as well as with a subduct-

F14. Hydrothermally altered basaltic lava *forms when seawater is circulated through hot oceanic crust. Brown and green clay, zeolites, and iron oxides replaced the primary minerals. This metabasalt now has hydrous minerals and the iron is oxidized. When such rocks are subducted they release a fluid that triggers subduction zone magmatism which is key to forming the continents.*

ed sediment component) and becomes hydrous and oxidized as well.

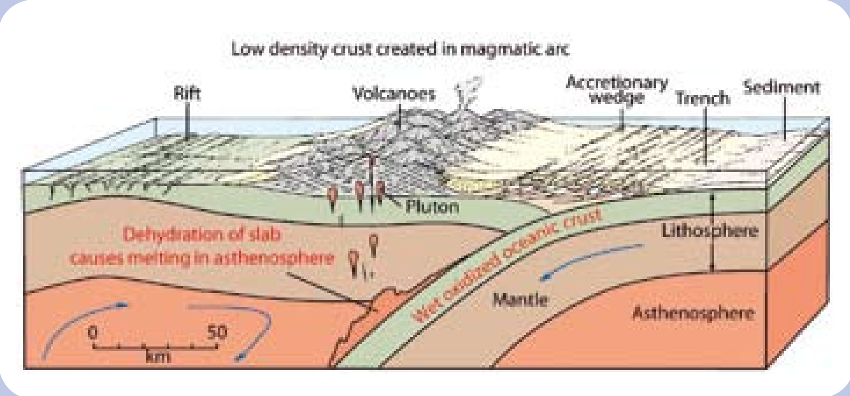
The water and oxygen play a dramatic role in the magma produced. Various experiments have shown the importance of water (Sisson and Grove, 1993; Hirose, 1997; Blatter and Carmichael, 2001) for generating silica-rich magmas (andesites) from the mantle wedge above a subduction zone. Water changes the proportions of the various silicates that crystallize promoting silica enrichment trends during differentiation. Other experiments show that elevated oxygen fugacity, likewise, produces magmas that are richer in silica and poorer in iron than those that evolve at low oxygen fugacity (e.g., Berndt et al., 2005). High oxygen fugacity stabilizes minerals that require oxidized Fe such as magnetite (Fe_3O_4). It is important to remember that this high oxidation state is unusual for planets and is entirely due to the evolution of plants that use photosynthesis. As a result, most planetary magmas, and even terrestrial magmas formed in non-subduction settings are less oxidized and magnetite is not stable in primitive mantle-derived magmas. The release of abundant water into hot mantle rocks is also unusual, because on other planets subduction of wet slabs back into the mantle does not occur.

Hydrous, oxidized magmas differentiate along very different paths than dry, reduced magmas. Both of these unique subduction zone characteristics promote silica enrichment in residual liquids formed by fractional crystallization. This can be seen by comparing SiO_2 and FeO variations for magma series from two different tectonic settings in the western United States. In Figure 16, I have plotted the compositions of Neogene volcanic rocks erupted from the Snake River Plain of southern Idaho with Paleogene rocks erupted from and near caldera complexes in the Great Basin of Utah and Nevada. The Snake River Plain is presumed to be the track of the Yellowstone hot spot, which now underlies Yellowstone National Park in Wyoming. The Great Basin volcanic fields formed as a result of the subduction of the Farrallon slab beneath western North America. It is apparent that volcanic rocks from the Great Basin volcanic fields follow a differentiation trend marked by continuous silica enrichment and a progressive drop in FeO* (total Fe calculated as FeO). This is a typical differentiation trend for arc-related magmas and is variously called calc-alkaline or magnesian. On the other hand, volcanic rocks from the Snake River Plain follow a classic tholeiitic differentiation trend. Mafic magmas become FeO-rich and SiO_2-poor with differentiation until the concentration of FeO* is about 18% and then the differentiation trend turns around and FeO* drops as SiO_2 increases (e.g., McCurry et al., 2008; Christiansen and McCurry, 2008). Important differences between these two magma series are, of course, their oxygen fugacities and water contents. The Great Basin suite is oxidized and wet compared to the reduced and dry magmas of the Snake River Plain.

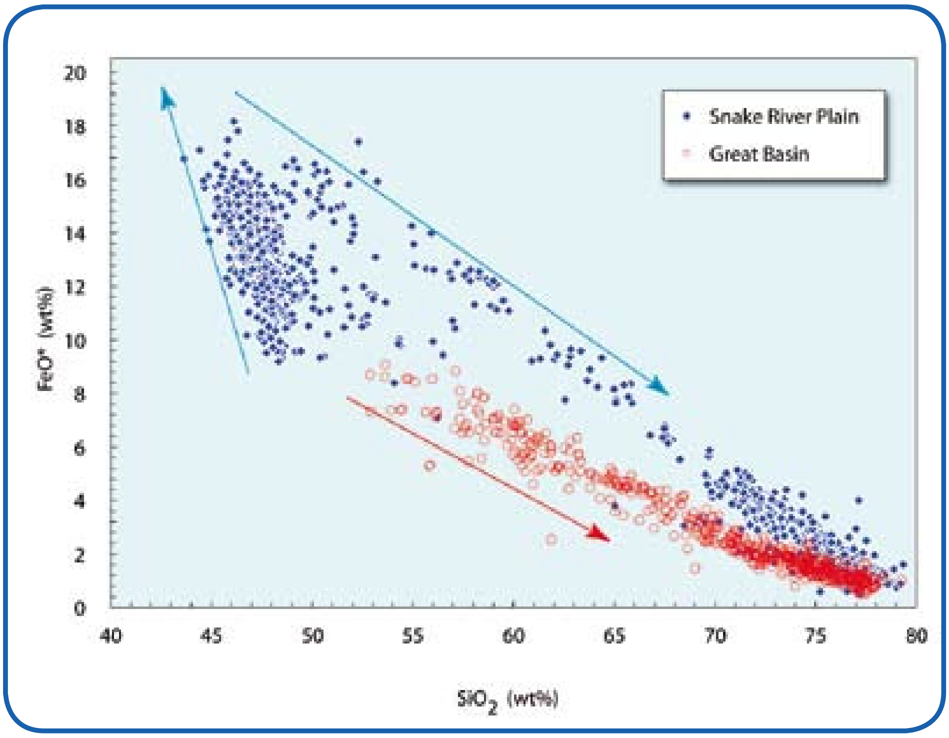
An important feature of these differentiation series is the density of the residual liquids (Figure 17). Densities calculated using MELTS (Ghiorso and Sack, 1995) increase with increasing iron content and reach as high as 2.9 Mg/m3 for the Fe-rich basalts of the Snake River Plain. The wet, oxidized differentiation series follows a trend of continuous density decrease as a result of the combined depletion of Fe and increase in SiO_2.

Thus, it is difficult to produce large volumes of silica-rich, low-density residual liquids by differentiation of Snake River Plains type magmas (Figure 18). Assuming closed system fractional crystallization, the proportions of residual liquids can be estimated along these fractionation trends. Along the Snake River Plain differentiation trend, a residual liquid with about 62% SiO_2 would represent only about 6% of an original basaltic magma. On the other hand, approximately 50% of a parental subduction zone magma might be left when the evolving magma reaches 62% SiO_2, the average for continental crust (Condie, 2005). A first order model for the evolution of Earth's continental crust would be the step wise accumulation of multiple batches of these lower density, differentiated magmas that originally formed in subduction zones. Island arcs, thus formed, could then collide and by lateral accretion make larger and larger continents.

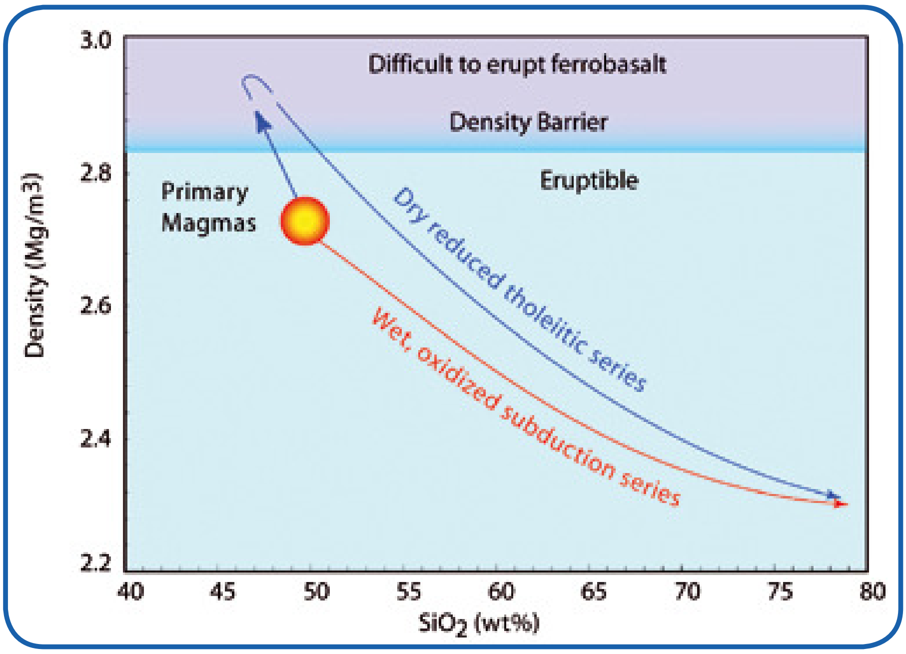
About 2.5 Ga, near the transition from the Archean to the Proterozoic, a major change in the volume and composition of continental rocks occurred (Figure 19). Continental rocks older than this are marked by relatively sodic felsic rocks mixed with mafic basaltic materials; the sodic rocks form a distinctive assemblage of tonalite-trondhjemite-granodiorite, the so-called TTG suite. Continental rocks younger than about 2.5 Ga are dominated by more felsic K-rich granites (Taylor and McLennan, 2005). It may be more than coincidental that the rise of an oxygenated atmosphere also occurs at this same time (Figure 12). The Archean-Proterozoic boundary may mark the time when modern style plate tectonics and an oxy-



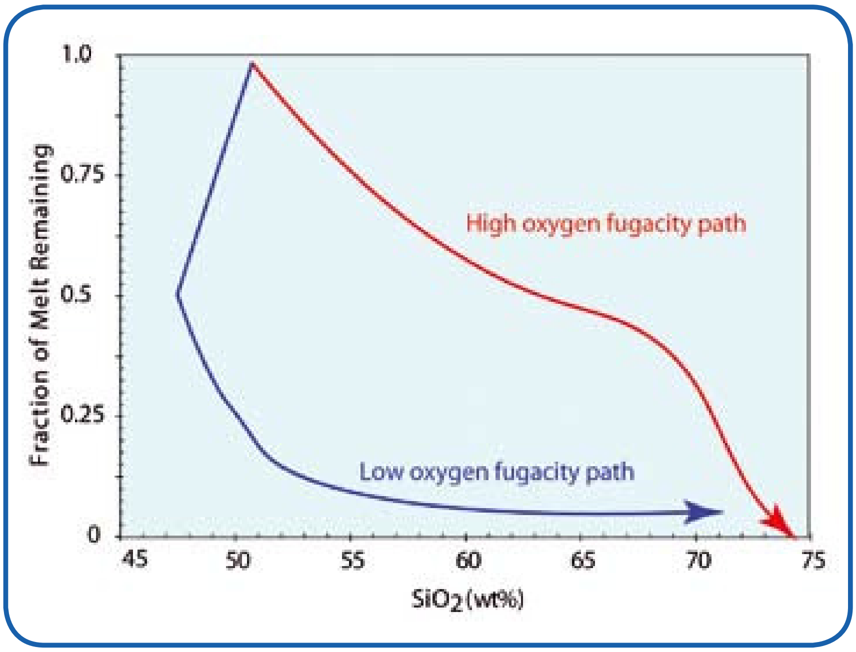
F15. Subduction zones *form where dense oceanic lithosphere returns to the mantle. Low density, silica-rich magma is generated by a chain of events that starts with dehydration of the oceanic slab. The buoyant fluid rises into the overlying mantle and causes partial melting. The wet, oxidized magma that is produced can differentiate to high silica magma. The magma accumulates to form a volcanic arc that can grow into a full fledged continent by tectonic accretion as well as by continued magmatism. (Modified from Hamblin and Christiansen, 2004)*



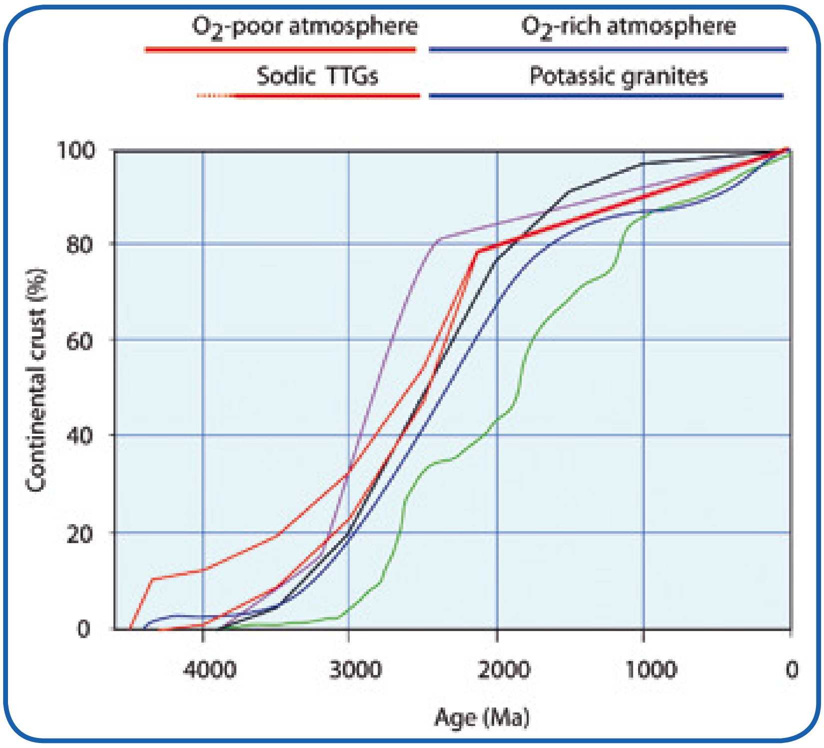
F16. Silica enrichment trends *develop during the differentiation of subduction zone magmas because they are wet and oxidized. They are represented here by volcanic rocks from the Great Basin of the western United States. Dry magmas with low oxygen fugacities differentiate to lower silica and higher iron, but when iron-oxide minerals precipitate, silica becomes enriched as iron declines. The plume related volcanic rocks of the Snake River Plain which is related to the Yellowstone hotspot differentiate along this trend.*



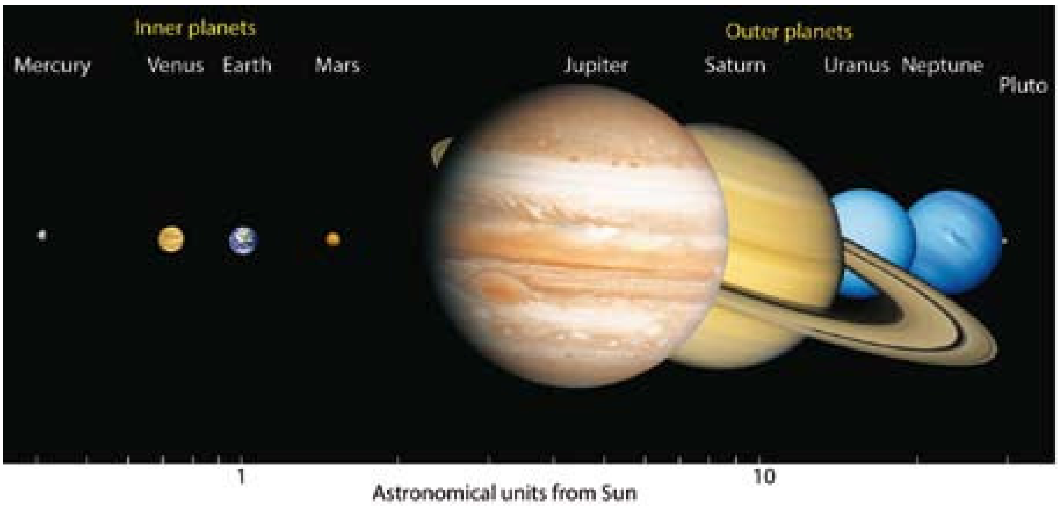
F17. The density of differentiates *along these two trends are also very different. Subduction zone magmas continuously decline in density, mainly as a result of the fractionation of Fe-oxides. Such low density magmas can accumulate to make silicic continental crust.*



F18. Oxidized magmas *produce a greater silicic magma with less fractional crystallization than do dry, reduced magmas. Many educed magmas initially fractionate on a silica depletion trend making the production of voluminous low density silicic magma less common than in oxidized, subduction zone suites.*



F19. The growth rate of Earth's continental crust *is poorly understood. However, several recent interpretations suggest that crustal growth accelerated between 3.0 and 2.5 Ga. This time period is also marked by the oxidation of the atmosphere and a switch in the dominant type of felsic intrusive rock from sodic tonalite-trondhjemite-granodiorite (TTGs) to potassic granite. Compiled from Rollinson (2007) and Condie (2005).*

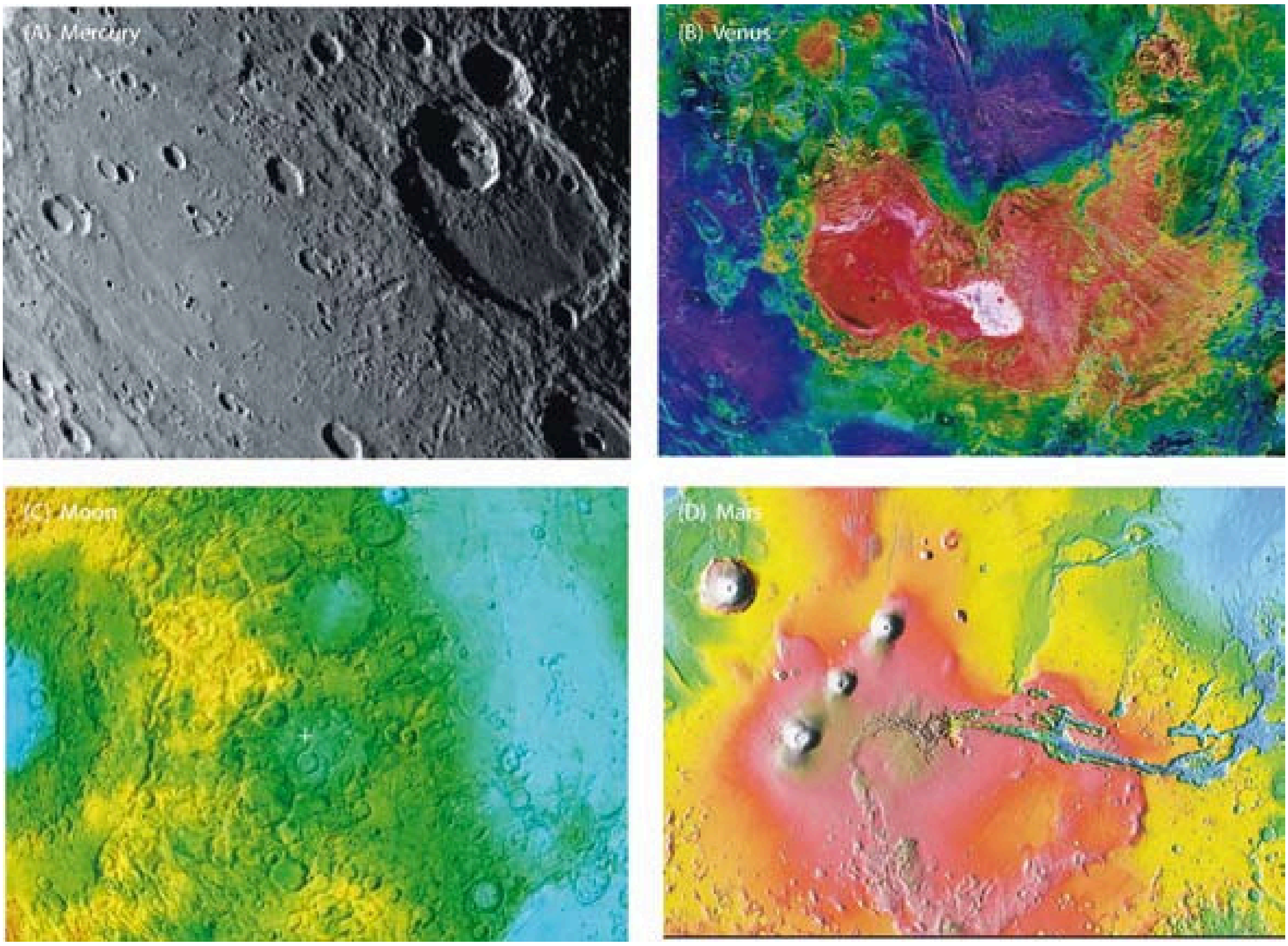


F20. The inner planets *are small, dense, and composed of silicates with iron cores. The outer planets are large and consist largely of hydrogen and helium. They have large systems of satellites that orbit them.*

gen-rich atmosphere combined to created large volumes of continental crust with a "modern" composition. Modern style plate tectonics may have begun in the late Archean when the oceanic lithosphere was cool enough to lose its buoyancy and be able to sink back into the mantle–with the help of a garnet eclogite sinker. As a result, oceanic crust altered by the circulation of hot, relatively oxidized water was delivered by plate subduction into the mantle. Because the fluid released by dehydration was also oxidized and water-rich, magma produced above the subduction zone evolved to form K-rich granite of the continental crust. Mafic cumulates remained in the mantle or delaminated from the base of the crust back into the mantle.

Why didn't continents form on other planets?

Campbell and Taylor (1983) summarized the origin of Earth's continents in this memorable duality: No Water, No Granite; No Oceans, No Continents. The uniqueness of the Earth has been emphasized in this scenario of the interdependent evolution of a planet's important geologic systems–its hydrosphere, lithosphere, biosphere, and atmos-



F21. The surfaces of the inner planets *are dominated by impact, volcanic and tectonic features. (A) Mercury has a surface dominated by ancient impact craters. Some have been buried by volcanic plains and deformed by small amounts of thrust faulting. (Messenger image: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington) (B) Of all the planets, Venus has features that most resemble Earth's continents. This is a radar image color shaded for elevation. Ishtar Terra is a large highland with relatively steep sides that is highly deformed. However, rock analyses for the planet and other evidence suggest that these highlands are not granitic like Earth's. (NASA, World Wind) (C) Mars has broad domes with fractures, faults, rifts, and large shield volcanoes as seen on this color shaded relief map of the Tharsis region. These features may be linked to a large, long-lived plume beneath this region. No sign of plate tectonics has been found on Mars (NASA, World Wind). (D) The Moon is much like Mercury. It has preserved ancient impact craters but some are buried by floods of basaltic lava like the smooth lowlands (blue on this colored shaded relief map) (NASA; World Wind).*

phere. Truly, these systems evolve together. Let us now review the characteristics of other planetary bodies and see why they did not follow paths to life and continents (Figure 20).

Mercury, the closest planet to the Sun, is too small (~4900 km) and volatile-poor to sustain even the beginning steps in the series of events that led to extensive differentiation, life, and continents (Figure 21). It formed so close to the Sun that volatile compounds did not form as solids and were not incorporated into the planet. An alternative theory calls for Mercury's accretion of water-bearing materials that were subsequently blasted off in a late impact that stripped away hundreds of kilometers of its outer layers.

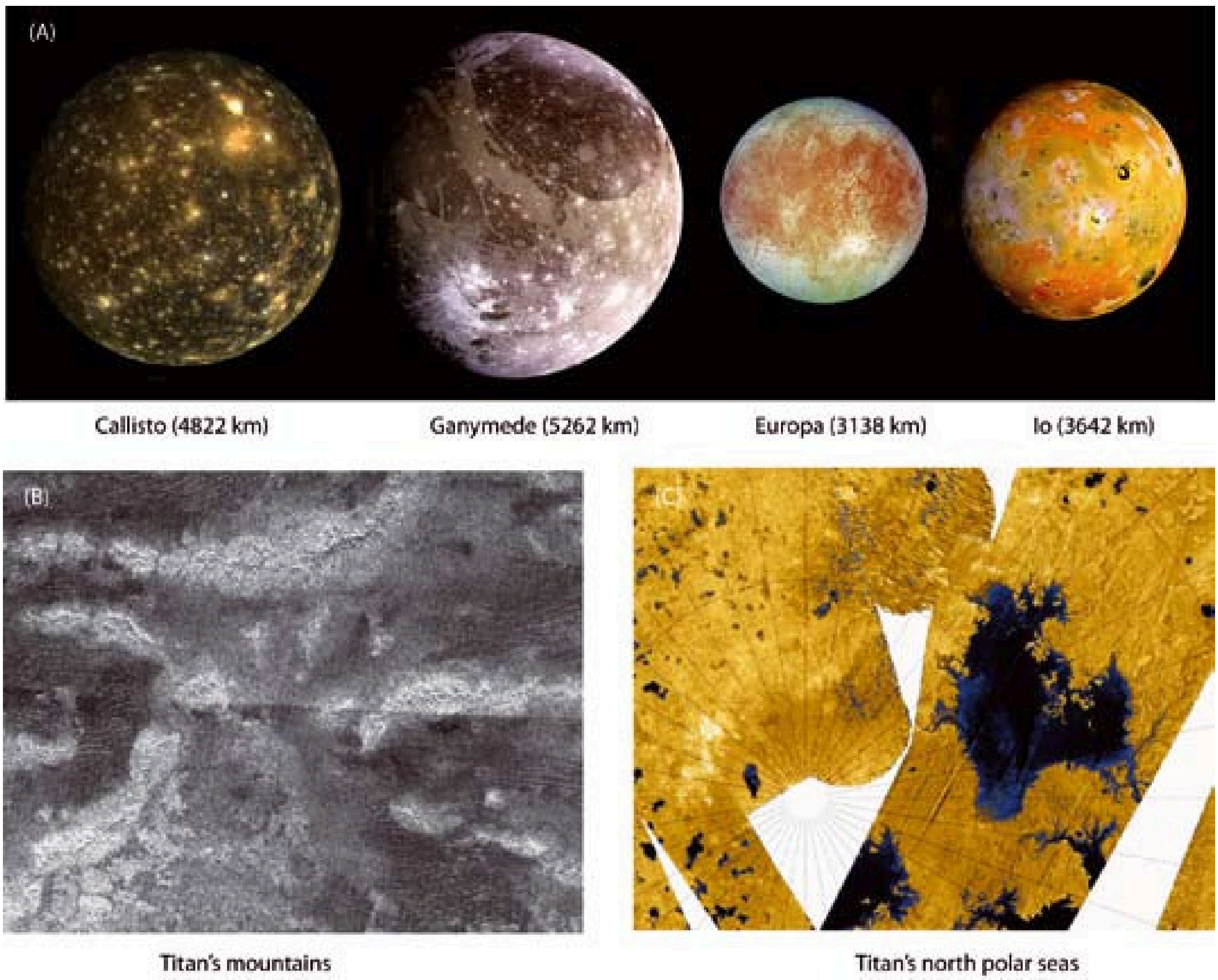
Venus is nearly as large (~12,100 km diameter) as Earth (~12,800 km) and would seem to be a planet that might have sustained a long-lived tectonic system (Figure 21). Venus does not have many impact craters; its surface is young (<500 Ma). Does this mean it has the potential for extensive differentiation and the development of silica-rich continents? No strong evidence exists that this happened. All of the chemical analyses of rocks sent back to Earth from the Venera landers were basaltic. Shield volcanoes and vast lava plains mark its surface and were probably formed by basaltic volcanism. There are no signs of plate tectonics on the volcanic plains–no symmetrical ridges like Earth's ocean ridges, no graceful pairs of volcanic arcs and trenches, no linear belts of mountains, and no hot spot tracks showing a moving lithosphere. Even its highlands–Ishtar Terra and Aphrodite Terra–appear to be crumpled, tectonically deformed basalt. Silicic magmatism does not appear to have been common. Why not? The lack of a hydrosphere and an oxygenated atmosphere coupled with no plate tectonics seem to be the root cause. Several investigations conclude that Venus once had water, but because it is closer to the Sun and its high surface temperature higher than Earth's, water vapor did not rain out but remained in the atmosphere until it broke down by photodissociation. The light hydrogen escaped to space and the left over oxygen combined with surface materials (e.g., Ingersoll, 2007). The dehydrated planet had no opportunity to develop an ocean or life and the lack of water in the interior may have prohibited the development of a shallow asthenosphere and thin plates of mobile lithosphere. Since no oceans formed, carbonate deposition could not diminish the vast store of carbon dioxide in its atmosphere. Venus is just too dry–no oceans, no plants, no plate tectonics, no continents.

The Moon, with its small size (~3400 km in diameter) and anhydrous composition, probably never got very far on a path toward extensive differentiation (Figure 21). The Moon's purported "seas" are made of lava that flowed 4 to 2.5 Ga. They lap on to "shorelines" defined by mountains made of coarse-grained igneous rocks that accumulated 4.5 Ga when the Moon was covered in an ocean of magma.

Mars, on the other hand, is larger than the Moon and had a protracted tectonic history (Figure 21). Moreover, it was probably not limited by a lack of water. Surface features include evidence for ancient rivers, lakes or seas, glaciers and icecaps, abundant groundwater, and meteorites that were tossed from its surface by impact and eventually delivered to Earth also show signs of the activity of water. Mars is apparently volatile-rich, but its small size did not sustain a long-lived tectonic system or the development of plate tectonics. Orbiting spectroscopic studies have found only very limited evidence for quartz-bearing rocks exposed at the surface (Bandfield et al., 2004). Vertical tectonics does not seem to be able to generate much silicic material, even though partial melting of wet mafic rocks that subsided into the interior is theoretically possible. Another limitation may have been its lower surface temperature compared to Earth. Temperatures may have been warmer in the past and its atmosphere thicker, but oceans have not existed for billions of years. Instead, water is frozen in ice caps or in ground ice. Thus, complex oxygen-producing life forms probably never evolved and the atmosphere of Mars remains CO_2 rich.

Even the largest asteroids, which orbit between Mars and Jupiter, are too small to have developed long-lived tectonic systems. Ceres (~980 km in diameter) and Vesta (~525 km) are large enough to have pulled their masses into nearly spherical shapes and internal melting undoubtedly occurred on Vesta, but they lack atmospheres. We lack detailed images of the largest asteroids, but discovery of liquid water on their surfaces would be very remarkable.

The satellites of the giant planets are other places to look for evidence of extensive planetary differentiation and the development of continents (Figure 22). However, only four satellites are about the size of or larger than the Moon–Titan (the largest moon of Saturn) and three of the four galilean satellites of Jupiter (Io, Europa, Ganymede, and Callisto). Of these, only Ganymede and Titan are as large as Mercury. Their small sizes would suggest rapid thermal evolution and a present cool condition. However, in some cases, the orbital environments of these satellites have produced tidal heating and have sustained tectonic systems that still operate today on Io, Europa, and probably Titan as well. All three of these satellites have very young surfaces. Io has active volcanoes and probably has internal plume-like convection, but no significant atmosphere, no liquid hydrosphere, and no sign of plate tectonics. Europa, in contrast, is water-rich and has an outer icy layer a few hundred kilometers thick floating on top of a liquid water ocean. Here, many of the prerequisites of life have developed; with liquid water, an underlying silicate layers, and thermal energy, some type of life may have evolved. Although oxygen has been discovered in a very tenuous, and perhaps even temporary, atmosphere (Hall et al., 1995), the oxygen is thought to have formed by the chemical breakdown of water with energy from the Sun, not by organic activity. But could a system of plate tectonics have evolved on Europa's sea floor, producing lithospheric spreading with attendant subduc-



F22. Some of satellites of the outer planets *are as big as Mercury and they have varied surfaces but no clear indications of plate tectonics or the growth of continental crust. (A) The four Galilean satellites of Jupiter, shown in order of their distance from Jupiter, are quite different from one another. Callisto is a simple cratered sphere with a thick icy outer shell. Ganymede has preserved some craters, but some form of tectonics destroyed some of the ancient crust. However, its surface is not as young as Europa's fractured icy layer. The innermost moon, Io, is tidally heated and has abundant volcanoes, but it does not seem to have developed plate tectonics. (NASA) (B) Titan is a moon of Saturn. It has a nitrogen-rich atmosphere and lakes and rivers of liquid methane on its surface. (NASA/JPL) (C) Titan also has mountainous ridges a few kilometers above its plains. They appear to have formed by some sort of tectonic process but were than dissected by fluvial erosion. (NASA/JPL)* tion and generation of evolved silicate magmas? If so, its thick icy outer shell has hidden it from detection. One possible limit on the development of plate tectonics on Europa would be the great depth needed to stabilize garnet, which may be needed to drive efficient subduction of crustal material. With the low gravity of Europa, garnet would replace plagioclase in a hypothetical basaltic crust only at depths in excess of 300 km. Such a thick crust seems unlikely. Even the crust on the extensively differentiated Earth is 8 to 70 km thick.

Titan, Saturn's large satellite, is similar in many ways to Europa (Figure 22). A thick icy shell overlying a layer of aqueous liquid is thought to envelope a rocky interior dominated by silicates. Titan has a nitrogen-rich atmosphere with nearly the same pressure as Earth's. Titan also has a "hydrological" system–with lakes, seas, rivers, subsurface fluids, and deposits of ice (Stofan et al., 2007). Temperature variations across the surface define climatic zones where different types of processes dominate. The equator is warm and dry with vast sand dunes; the poles are cooler and wetter with small seas dotting a karst-like landscape. The main difference between Earth's hydrologic system and Titan's is that the working fluid is not water, but methane which is a liquid at this distance from the Sun. No sign of an organized plate tectonic system has been found on Titan yet, though mountains (Radebaugh et al., 2007) and even volcanic features (Lopes et al., 2007) have recently been reported.

From this comparison it seems that plate tectonics is critical for the generation of silicic continents. An obvious question then is, "Why didn't a system of plate tectonics develop on other planets?" One of the prerequisites for plate tectonics must be a shallow asthenosphere to promote the definition and movement of lithospheric plates. A shallow asthenosphere may be a function of the planet's water content. Even small amounts of water can weaken mantle rocks and lower the melting point by hundreds of degrees. In the absence of water and a shallow asthenosphere, the lithosphere may have no sharply defined base and the lateral motion of thin plates might be prohibited.

Conclusion: The Importance of Place

What lessons about Earth have we learned by studying the planets? Earth is unique, even when only a few of its major features are considered. It has a dynamic biosphere, an oxygen-rich atmosphere, few meteorite impact craters, oceans of water, and high-standing continents. It seems likely that Earth is the only planet in our solar system with silicic continents. By focusing on the generation of silicic, buoyant, continental crust, we might formulate a simple recipe for this unique planet we call home. Take one large silicate planet, add water, and heat carefully for 4.5 billion years. This recipe might be sufficient to trigger the chain of events outlined above and lead to the generation of a differentiated planet with oceans, oxygen-producing plants, an oxidized atmosphere, hydrosphere, and ultimately lithosphere, plate tectonics with subduction and sea-floor spreading, and ultimately generation of hydrous, oxidized magmas in the narrow wedge of mantle above subduction zones.

The principal limitations for the development of continents on other planetary bodies are listed in Table 4 and generally can be tracked to an inappropriate size and a lack of liquid water. These two simple features of a planet are largely controlled by its ancient accretion history. In this creation myth, the key lesson is place–the construction of a planet at just the right distance from the Sun, with the right mass, the right mix of materials, and the right input of solar energy. All of these features are based on the fateful place where Earth formed in the solar nebula 4.5 billion years ago. As a result, oceans, life, an oxygenated atmosphere, and plate tectonics emerged and led to the development of continents as we know them–these islands where intelligent life evolved and thrived.

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