GeoJournal 19.2 207–220
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A Planet-Bound Model for Origins of Life, Including Pre- and Retrodiction

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Planetary Evolution Near Our Sun

Geophysical history quite likely puts some very powerful constraints on life's evolutionary emergence on Earth. *If* life self-organized in a time slot near 3.8 thousand million years ago (3.8 Gya – numbers indicating time will be expressed in the Gy scale) on Earth, *then* we can imagine what some of those constraints were. They consisted of perhaps 7–9 independent process startups ("clocks" or clocking processes) that had to take time and have place before life started (Iberall, Soodak (1)). These were effectively a serial sequence drawn from such processes as the formation of a solar nebula, planetary accretion, planetary degassing, planetary physical-chemical layer formation, planetary solid skin formation, water sequestering and phase condensation, formation of a mature gaseous atmosphere, regional plate formation by cracking of the surface skin, plate tectonic movements both vertical and horizontal, volcanism through the cracked or weakened surface (e.g., weakened by stresses or meteoric bombardment), formation of a mature hydrological cycle, extension of a hydrological cycle of erosion of plates protruding above water level, life's formation as the resultant of a heterogeneous catalysis within sedimentary erosion materials at the triple interface of porous solid land, liquid water, and gaseous atmosphere. In our opinion, the alternative of a homogeneous catalysis, e.g., pinpointed via the common metaphor of a 'soup', has vanishing small probability in any physical-chemical process competition. In crude approximation, we have viewed the serial processes as each having taken a period on the order of 0.1 Gy to have developed. Thus, we estimate the interval 4.6 to 3.8 Gya to have been a very busy time frame filled virtually with a forced sequence of many serially ordered steps.

To provide greater detailing of hypotheses and evidence for these steps and their ordering, a sketch of the kind of proof needed for such 7–9 process step startup, we begin with an article (Taylor (2)), which provides the following pertinent conclusions of a recent conference assembled to achieve agreement, if possible, about the history of the early Moon:

1. There existed a primitive solar nebula.
2. There began "some early high-temperature event in the primitive nebula" close to 4.56 Gya [according to current physical thought, such a potential process would be the work of a compressional shock in a spiral galaxy, an idea that C. C. Lin introduced in the 1960's. To start a nuclear reaction going, the nominal magnitude of such gas dynamic heating involves an initial heating to perhaps 100,000° K or greater].
3. Following the depletion of volatiles (e.g., those materials volatile below 1,000° K), Venus, Earth, Mars "formed from a suite of precursor planetesimals", from which they accreted, "a process taking perhaps 100 million years." Thus the geophysical community have established a reasonably defensible picture for the first two clocks, bringing us now close to 4.45 Gya (for additional background detail, see also Dermott (3)).

Having established or anchored some reasonably sharp estimate for the timing of the first two clocking processes, we can now go on to a discussion of the remaining 7 or so process startups. That is, we wish to sharpen up the estimates that we made first in 1979 (17) by additional guidance from (2) and other references. As the argument progresses, it will be seen that we are attempting to hold the temporal precision of our account, if we can, to within a very few units of ± 0.05 Gy.

4.45 Gya – Volatiles having been depleted from the colder noncentral matter of these planets (2), what is then feasible are surface, e.g., proto-earth, temperatures in the vicinity of 1,000° K, so that such volatiles are only available in a gas or vapor atmosphere surrounding such planetary and planetesimal material-sequestered 'droplets' (condensations of liquid and solid form) that may have formed from distributed rings of material in a disc-like planetary nebula. Depending also on the luck of the sequestering draw from the nebular disc and rings, these droplets would exhibit an initial separation of materials of different constituents and densities. From the prior cosmological physical and chemical processes, we accept the existence of the major hydrogen-helium constituents of cosmology, an early first generation of metal-poor star formation within galaxies, the fast-slow nucleosynthetic processes in those stars that produced the very small residue of other nuclear elements, nova and supernova explosions that peppered the galaxies, a second generation of nebulae and stars with their new 'metallic' atomic constituents relatively rich up through iron, and the beginnings of a relatively cold (under 3,000° K) atomic-molecular chemistry among planets and planetesimals particularly rich in condensed compounds like water-bearing compounds, carbonaceous and silicic compounds, and other 'metallic' segregations moderately rich up through iron compounds. While theory exists for the nature of the distribution of atomic and molecular type materials among the near and far planets, it is not particularly sharp or differentiating among the closer planets. Thus we have to depend on an empirical base of still somewhat dubious knowledge. For example, geophysicists (illustratively, see Robertson, Hays, Knopoff (4), Windley (5), Smith (6)) generally accept that the luck of the draw brought together iron-nickel core material separate from silicic outer material for their inhomogeneous joining and sequestering as Earth; iron sulfide for Mars' core; also that a nominal temperature by the time of that initial localized sequestering was of magnitude 1,000° K whether the continued accretion of planetary material was from a hot or cold start (or, if one wished to be more conservative, one might estimate Earth core temperature subsequent to accretion to be as high as 1,500–1,800° K. It is not obvious what the segregation of energy, momentum and angular momentum will be in the nebula, only their overall conservation. It had been common to assume that temperature varied with distance in the nebula, but that view is changing. Thus the distribution measures are not well constrained. Both a hot and a cold accretion is possible, with the subsequent gravitational infall of material determining the post-initial thermal process).

A reliable theory for planetary composition out of the primordial nebula is still out of the question although it is beginning to be approached with increasing constraints. For example, a recent article (Stewart (7)) asserts, with considerable boldness, that "A sound theory of planetary formation should predict the observed masses of the planets, their bulk chemical composition, the spacing between their orbits and perhaps the number of their moons." In attempting to account for the exceptionally high density of Mercury, with an iron-to-silicate mass ratio twice that of other terrestrial planets, the article reviews the older isolated feeding zone (each a ring of material) theory for the accumulation and formation of each planet and a more recent simulation model of planetary formation from a swarm of several hundred colliding, lunar-size planetesimals. For example, the planetesimal hypothesis has been invoked most recently to offer an account for the origin of the Moon by the impact of a large early planetesimal with the Earth in a time frame prior to 4.4 Gya (Newsom, Taylor (8)). Neither of the accretion models are definitive, yet clearly the planetesimal theory is on the way in offering capability to deal with some of the physical puzzles (e.g., distribution of matter, density, angular momentum, and rotational axes) found in the solar system. We will continue to appeal to the much more ambiguous noncommittal concept of 'luck-of-the-draw', as far as material constitution is concerned.

4.35 Gya – Given a luck of the draw for fairly similar but not identical materials on the three sister planetary droplets, Venus, Earth, Mars, with differences for Mercury and satellite Moon (as mentioned, theories for the characteristic segregation with radial distance in the nebula are not meant as yet to be sharp in the sequestering), we recognize the existence of a subsequent cooling process that would take the surfaces of these three planets down to interesting temperatures below 1,000° K, say in particular to the critical temperature of water, about 370° C, and its vapor pressure of about 200 atm. Because of the difference in sizes and radial orbits around our sun, we recognize that the processes on these three planets and our Moon satellite are not going to be identical. In fact we learn from physical study that their separation distances are quite critical (e.g., Hart (9)), critical enough to create the "three bears" syndrome of not enough, too much and just right. Thus of the three sister planets, one loses its atmosphere (temperature that drops with atmospheric altitude in a very tenuous atmosphere – Mars), one has an atmosphere with a runaway greenhouse effect in temperature and pressure (temperature that increases with atmospheric altitude – Venus), and one has a pressure-temperature that is just right (temperature that nearly regulates, e.g., with a two lobed tropopause of fall and rise, and fall and rise in temperature – Earth). But these three more final stages only emerge much later. In this early phase, it is clear that one may lose light mass atomic components and also have under 1,000° K recondensations of some volatiles, creating a condensation involving both an atmosphere and hydrosphere, in fact transition also to atmosphere and solid skin surface. If we look through all interesting simple compounds from the first few chemical families, it is not surprising to stumble across the relatively high critical and triple points of water, and then carbon dioxide, and also some simple hydrocarbons. Thus there is no reason that water may not be a first relatively high temperature stopping place, if both compound and abundance are of concern to the determination. So we are easily willing to conclude, from experimental fact, that water did win early on Earth and Mars, and that carbon dioxide did win on Venus and ultimately on Mars (e.g., on Venus within range of the critical pressure of carbon dioxide, but higher; on Mars now near the triple point of carbon dioxide). Beyond the three sisters, it appears likely that hydrocarbons won on Jupiter for its outer condensed surface. The point is that if and when any such two phase near-equilibrium is passed, with sufficient energy storage, that condensible surface process can and will act as a crude thermostatting reservoir of surface temperature. Thus we elect that to be the case, involving surface water storage, early on Earth and Mars. Because of their difference in size, we do not expect the time scale for cooling to be precisely the same, even if the nominal time frame is in the vicinity of near to but less than 4.45 Gya. We typify the cooling and regulating process (i.e., into the liquid water regulating range) by a 0.1 Gy estimate (guess is the better term here) for Earth-Mars. The important point is that at this time frame in planetary history we have identified a rather sharp marker that if – as on Earth and Mars – there is a hot heavy liquid or solid metallic core (iron-nickel for earth; iron sulfide for Mars) sequestered from a hot fluid silicic mantle, the surface-core temperature differential would guarantee the beginning of Bénard cell rolls. From core temperature estimates, one would estimate a roll time (Turcotte, Burke (10) for Earth, probably pursuing the Russian empirical thesis of plate epochs – see Beloussov, (11)) for Earth and possibly Mars (?), of about 0.3–0.6 Gy, a value which can be sharpened up to about 0.6 Gy (from Vail's data on the variation of sea level height for the past 0.6 Gy (12); see also Iberall's account (13, 14) for the geological column, a confirmation of Beloussov's model scale hypotheses – Beloussov's data suggest a relative sharp estimate of about 0.45 Gy, so that we can settle comfortably on some value between 0.4 and 0.6 Gy for Earth rolls).

4.25 Gya – Further cooling below the critical point of water, 374° C, moving toward the triple point of water of 0° C with its low vapor pressure (e.g., 4 mm Hg), would have acted, in part, as a regulator of surface temperature (temperature would have been regulated by the condensation and formation of clouds in a meteorological system composed of residual 'volatiles', e.g., on Earth and nearby planets, gases such as nitrogen, carbon dioxide, or hydrocarbons). Pooling of liquid on the surface thus also would take place. On Earth and Mars, luck of the material draw made water pooling appreciable by this date. Given the differential temperatures of a fluid internal mantle, a solid skin with its surface regulated by a second cooler fluid surface layer, with both fluid layers involved in convective heat transfer processes, it is quite plausible that straining or cracking of the solid skin in local regions would take place.

Such regulative cooling and pooling of a condensible on the surface, almost certainly involving surface 'boiling' of the condensible between the convective gas and solid layers, given a vertical instability like the Bénard rolls inside, guarantee a Richardson instability in a gravity field and a strong atmospheric circulation by air mass cells, influenced of course by planetary spin as the emergent heat flow attempts to equalize (seen today on both Earth and Venus). One would begin a strong meteorological cycle as well as a hydrological cycle that are mutually entwined.

Thus by this time, e.g., 4.25 Gya, one could have the opposing processes of evaporation, condensation pooling of liquids such as water, and surface process of volcanic eruption as a squirting from cracks or plate margins of underlying fluid silicic magma. These, we surmise, would be basically similar processes on Earth and Mars, although we note again that the time to reach this process state did not have to be precisely the same on the two planets.

At this point, the Mars history remains marginal, juvenile, nearly fixed at this horizon, whereas the Earth story continues to move on considerably. What makes the difference here? It is our conjecture, another luck of the draw resultant, that the Earth's original sequestering involved the accretion of an appreciable fraction of the higher nuclear number radioactive elements. This endowed the Earth with a modest source of internal energy from radioactive conversion; in any case – because of the difference in size – of greater magnitude than any such process on Mars. This would drive a higher energy flux through the solid skin for Earth than for Mars. Both surfaces cracked, but the Earth's internal rolls were more vigorous, the surface disruption and volcanism was more vigorous. The result of this first generation of such plate cracking and stress relieving movements we choose to call "rock and rolling" (more literally roll and rocking. Note that the catch-phrase, rock and roll, is used simply to denote other than a first order symmetric strain mode of the planet's thin surface when some anelastic movements are involved). Namely, the rolling process in the mantle, plus thermal pluming, produced deformation and cracking of the surface (Earth and Mars) which permitted volcanism, and which forced these plates to rock in place. In fact, it appears that Mars' more localized rocking in place (Tharsis bulge) was more violent than Earth's (such roll and rocking processes should not be too difficult to model). The reader will note, in part empiricism, in part from back of the envelope estimates of the time scales required to sort out these processes, that we have alloted about 0.15 Gy to bring them into a mature recognizable state.

4.1 Gya – On Mars this sort of process state is to be noted by this time frame, and it persists afterward, loosely speaking, so fixed in later time. Thus rocking, of appreciable magnitude; surface bombardment from outside; shallow water pooling; mild atmospheric dynamics; mild erosion and sedimentation; mild braiding river systems that are both primitive and juvenile were frozen in, and could persist until the pooled water and atmosphere were lost (e.g., from a considerably lower value for gravity). Mars' processes are basically frozen into Earth-equivalent 4.2–4.1 Gya processes.

On the other hand, the drive on Earth (radioactive augmentation of heat flux from the iron-nickel core) through the surface plates drove a much more vigorous hydrological cycle among the surface water pools. A mature hydrological-meteorological cycle of considerable proportions emerged by 4.1 Gya. The filling of land indentations by such surface waters, the establishment of a mature meteorological cycle in the entwined composite took time. A time scale of 0.1–0.15 Gy to sort these processes out is not unreasonable.

4.0 Gya – Another 0.1 Gy of this strong roll cycle, with the countering process of a mature atmospheric stirrer, a mature hydrological stirrer, permitted the sustained internal roll process to couple more strongly into plate motion to where the initial rocking plate motion would produce sufficient additional stresses to begin to create a more mature accompanying horizontal plate motion as well. Plates climbed over plates; plates began to subduct; and rifts began to develop. As we shall discuss later, these processes could have been augmented by a vigorous infall of meteoric material at this time frame, which both weakened the surface and made it more plastic.

3.9 Gya – By this point, 0.1 Gy of vertical and horizontal plate motion and further cracking and recracking, coupled with mature hydrological and meteorological cycles, produced the capability for an eroding, sedimentizing, process. This, we have shown (Iberall (13, 14)), was a process with competence to extensively erode a protruding plate in about 0.1 Gy.

3.8 Gya – One process cycle of 0.1 Gy was then capable of producing the first generation of continents on plates, shaped thereafter with a sedimentized surface layer (and commonly also metamophosed upon subduction at some later time phase). Give or take 0.05 Gy (with not more than one or two such uncertainties – we are reluctant to assign errors to our estimates much more than one or two of these units), we have attempted to show that our model arrives right on time for the earliest known sequence of rocks on Earth. Namely that some such Earth surface status would have to be reached by what effectively was an obligatory serial process.

This modeling has been based on combining the work and ideas of a considerable number of investigators. It includes my interpretation of their work, and a number of studies and integration of ideas that I and some colleagues have performed. I have attempted to be scrupulous in referencing material. Other readers may interpret some of the referenced material different than we have. But we want to go beyond this and show why this accounts for the beginning of life on Earth.

The process of creating sediment produces a very elaborate surface chemistry. At the point we have reached, we have three powerful stirrers at the triple interface of gas (atmosphere), liquid (hydrosphere), and surface porous solid (sedimentary solid). *The gravitationally and thermally driven hydrological cyclic process courses through these three phases of matter. It dissolves and leaches out all 'solvent-volatile' components from the Earth's surface using the meteorological precipitation of rainfall, consequent ground water flow, rivers and bedload delivery of both mechanically and chemically abraded ingredients, with their deposition in pools and oceans. After passing through the almost infinitely-graded resorbing porous medium of the sedimentary ground, that passage constitutes a 'trickle bed' with every process time scale from seconds to millions of years and every space size scale from fractional micrometers to boulders.* That cyclic trickle process guarantees reaction sequences in reaction coordinate spaces. What kind? Every kind of silicic and carbonaceous reaction sequence that may be involved, most particularly, in reactions with water. If a biochemical life sequence is to be found among the ingredients available at that time, it will and did find its coordinate scaling. What might be the time horizon for such physical-chemical complexification? On Earth, we find it to be 3.8–3.9 Gya. With this physical introduction, we can now turn toward some actual detailing notion on how life may have started on Earth.

Life's Evolution

To provide more of a scenario-like mechanistic flavor to the proposal that the biochemical startup of life piggybacked on the geophysics-geochemistry of the first sedimentizing of plates on Earth by a hydrological cycle during a narrow 0.1 Gy slot 3.8 Gya, in the model spirit of this paper the following depiction is offered: Its ingredients are drawn from current speculation (we elect Yates (15), particularly chapters by Morowitz, Orgel, Schuster. These authors adequately represent most of earlier conferences and researches devoted to the same topic of origins of life).

1. We start from the premises that the early phase of the Earth's atmosphere was heavily reducing chemically; and that the liquid phases on the Earth's surface contained hydrocarbons (Hart (9); Brock (16)).

2. An insulating thin partition between two compartments of ion bearing water solvent creates excellent conditions for electrical charge accumulation and flow either as a battery or a condenser. Single or double layers of hydrocarbons are excellent examples of such partitions. They create excellent sources for transient or continuing chemi-osmosis (Morowitz, for example, continues to pursue an earlier enunciated theme that "the present day inputs into the biosphere are all associated with charge separation across lipid bilayers". For the relation of osmosis and separating flow bridges, see Soodak, Iberall (17)).

3. Even starting from the simple quartet of nuclear species – COHN – a reaction space, seen already in a gaseous phase, will develop such compounds as CH_4, NH_3, H_2O in a reducing atmosphere, and – as the reactions multiply – will tend to evolve, via a dominance of free radical reactions, "toward lipids through ethane and toward amino acids through the reactants for the Strecker synthesis: cyanide, ammonia, and an aldehyde" (Morowitz (18)). One can say that the general validity of some such reaction graph is borne out by the common reactions that have been found in galaxies, such as in gas clouds. The number of reactions now known from these galactic regions number in the hundreds.

4. The galactic reactions so far have not been found to reach to self-replicating chains. They are found in the form of chains of simple compounds, e.g., bases and sugars from COHN. But also other nitrogen-containing compounds would have been present. Many such compounds are found in carbonaceous meteorites. While there is a considerable gap to get to self-replicating molecules with that capability, the polynucleotide nucleic acids (RNA, DNA), do seem to form a chain that reaches down to the simpler compounds. That chain consists of the formation of the nucleic acid bases, the sugars, and their linking into nucleotides. Small chains of nucleotides can form (e.g., strings of perhaps 10) but the full problem for the origin of life is to get longer strings of perhaps 20–100 to form, and how to get these materials in appreciable yields, e.g., for example what might be used as catalysts without the existence of enzymes (Orgel (19)). The premise here is that long molecular chains do depend on catalysts for their long regular formation.

5. Possibilities do exist among nonorganic materials to serve as substrate, reactor bed, or catalyst. Both Katalchsky (20) and Orgel (19) have offered some encouraging demonstrations, e.g., the use of an alumina clay, the use of other metals such as lead, or perhaps zinc.

To form a scenario that connects to our ideas, we add that the physical scaling of a suitable reactor bed is the most important process to complete the chemical chains. Thus:

6. The formation of sedimentary rocks, i.e., of sedimentizing a continent-sized body on newly emergent plates, is a process that takes a significant fraction of 0.1 Gy. Because such a sedimentary system will produce unit pore or cellular scaling in that porous medium at every size down to micrometers and time scalings from seconds (surface ground flow processes) up to millions of years (deep ground flow processes), that trickle bed, when invaded or perfused by water, is self-selective and self-partitioning for any and every space and time scale as far as the dynamics of chemical processes is concerned.

7. At the triple interfaces of liquid – both inflow of ground waters with one set of chemical concentrations and ocean waters with another set of chemical concentrations, gas – the reducing atmosphere, and solid – the sedimentized earth as a graded and transformable substrate, there are a rich number of stirring force systems. These are the effects of cycles of wetting and drying, warming and cooling, light and dark, ionization and recombination, redox reactions in sequestered spaces, more generally all the physical processes of diffusion, wave propagation, and convection.

8. The chemical processes are thereby linked with a wide range of important physical processes both with intimacy and in all phases of matter. In particular, these processes are guaranteed to solubilize and leach ground ingredients, to condense gas reactions into the liquid phase and to promote reactions within the gas phase, as well as to sequester materials in the porous medium.

9. With more detail, there are both intermittent and continued flow systems (e.g., daily, seasonally, longer environmental processes such as those scaled by sun spots, by processes like glaciation, or as external meteoric inflows) passing through the sedimentized porous media in which cellular structures exist involving water-hydrocarbon interfaces (noting that these do not mix) and in which the basic temporal processes going on are ion exchange processes. A putative reason for assuming ion exchange is important. In relatively short time (short compared to 0.1 Gy), solubilizable ingredients (except perhaps for NaCl which can bed and dissolve repeatedly) may be expected to leach out of the earth by the ground waters. Thus the dominant physical-chemical process that might be expected to continue are ion exchange processes, typically involving zeolites. It is such materials which have flowed through the porous ground beds, and which interact in turn with the saline concentrating (earlier soluble component) ocean waters. Thus one is guaranteed both electrical activity, inorganic battery-like activity of current fluxes through the cells (chemi-osmosis) and a range of condensing organic materials developing in these sequestered media. Any primitive idea of what might be the osmotic streams is to be obtained from the relative difference of the oil-water partition coefficients, a salient measure of transport processes across current real or artificial membranes. Note, for example, that the problem which current simple life solves is how to make do with a series of processes in which water essentially always continue to leak into the cell. The thermodynamic death emergent from that process is avoided and resolved within the simple cell by repetitive splitting, albeit currently by using DNA-RNA. A primitive form of such splitting is merely the need to fill an oil-covered droplet sac with water until it, the sac, bursts and reforms into multiple droplets. This would happen if a reservoir of oily fluid is also available.

10. The important ingredient required for some operational capability to repetitively fill droplets from a trickling stream under an osmotic force, burst, and reform a hydrocarbon membrane nurtured by a some oily component in the stream, at some time scale however slow, we would believe, is the chemical evolution of a sequence of metallo-organic compounds carried within the trickling stream. It would be our surmise that here lies the initial ability to form and take on board catalysts and carriers. Now while there are many such metallo-organics that might form, what we are interested in are those that might act as both substrate, a catalyst, and a source for electrical transport. Note that we only need a slow catalyst, not one that matches the time scales of modern enzymes. Our porous medium reactor bed provides us with all space and time scalings up to as much of 25–100 My as are needed.

11. Life-derived morphologies in 3.8 Gya sedimentary rocks associated with iron have been shown by Pflug (21), Appel (22), Robbins (23), and Schidlowski (24). Since such early forms of life are already conjectured to exist, if not yet hard proven, and are certainly known later on, it is quite reasonable to infer that an Fe^2-Fe^3 transformation is certainly a major contender for filling the metallo-organic scenario. That is, an iron based metallo-organic could very well have been an early contender for acting as a higher ordering catalyst for producing polymerization-condensation chains associated with hydration in the early porous medium environment. Such a redox metal and the plausible processes named could have resulted in taking on engine-like characteristic (as a chemical battery) and/or perhaps material production and replicating characteristics. (Of course, there are other metallo-organic contenders, e.g., based on sulfur; based on proton pumps; based on photosynthetic pumping, the major contender favored by authors in the 1960's – see Fox (25) and Morowitz (26); based on manganese; plus other contenders). Taking aboard any one such initial step capable of energy pumping would seem to have projected life processes well on their way.

Later symbiotic processes could then have led to further chemical evolution to produce more modern catalysts (enzymes) that were 1000-fold to 10 million-fold faster. The development of 'motor' capability is not a highly significant step in early evolution. That could come after self-empowerment and self-reproduction had been taken on board.

12. What appears to provide considerable strength to the ideas developed thus far is an article in a recent book (Wong (27)). The author, pursuing petrochemical interests, studied laboratory and sedimentary rock porous media, particularly for both their hydraulic flow and electrical conductive characteristics. He shows that they exhibit fractal properties largely because of the fact that besides their solid and pore regions, there is a very significant sorbed boundary layer formed by the liquid transported material. Characteristically, he finds that the fractal surfaces in sandstones are due to the presence of clays. That surface boundary layer acts to produce an effectively negative surface tension. The effect of that property is to make forms and processes which are not minimum surface area volumes, e.g., spheres, but surfaces that are highly extended, e.g., fingered surfaces. That study provides some of the most exciting ideas of what can be promoted as catalysts in the kinds of porous media that are associated with sedimentization and the presence of both soluble and insoluble impurities. Ordinarily, in order to consider cooperative trickling streams of oil and water, one might have thought of requiring something like a detergent to achieve some near physical mixing. The catalytic capability of a clay to perform the process of affecting the unfavorable surface tension characteristics gives the scheme an enormous boost (The reader of Scheiddeger (28) may sense some of the feeling of excitement that we may have helped contribute to the theory of flow permeability in highly porous media, as it developed in the 1950's; studies which helped lead to us characterizing the proper boundary conditions in flow fields, e.g., those involving both gas flow (28) and liquid flow (29, 30), particularly important in fields involving small spatial scale. We make this observation to heighten the sense of our own reaction to the Wong study in extending such physical results to the additionally very rich physics-chemistry of boundary layers. No physical-chemical researcher of the 1940's could not have been unimpressed by the scope of Brunauer's studies in extending the theory of sorption of surfaces).

So what is to be noted in what we are saying is that at the critical 3.8 Gya time frame on Earth, we no longer believe that polymeric, catalytic, protein-based enzymes, and genetic code material were required for the first few steps for life's biochemistry (e.g., Oparin's ocean; precise matching of stellar output to a visual photosynthetic range; and the development of 'just so' chemical compounds). We suggest that the three phase interface, with warm-cold, charge-neutralization, water-oil, guarantee micelle scaling, and only requires a differential partitioning of flowing material to effect easy entry into and out of such cells. Such 'fingering' processes get around relatively strong surface tension forces, making it fairly simple to capture some metal ions with energy pumping capability. If and when micelles capture a suitable moiety that can exist in two different energy states, then chemi-osmosis by vesicular transport, or tunneling transport can put energy on board the micelle. Formal reproduction is not necessary. That energy can further chemi-osmotic engine processes and the manufacture of additional chemical units. The three matter phase processes may then continue to drive such 'sheets' of cellular units without the 'luxury' of unit reproductive division. Primitive reproduction need only consist of a one-way internalizing flow of one half of a chemi-osmotic flow (influx of water) and a second half devoted only to extending the sheet of such micelles. As complexity continues to build up in the internal manufacturing process, ultimately the process may produce reproductive processes for membrane extension, e.g., lipids, for reproductive division, and for a reticulated network of reproductive function storage as well as storage of other internal modal functions. Thus Orgel's and Eigen-Schuster's (see Schuster (31)) polymeric process developments are not a first required result.

The reader who wishes an up-to-date "soup" (homogeneous catalysis) view of life's origins and the problems that such a view entails can find it in the latest edition of Watson (40), Chapter 28 "The origins of life". In the case that one wishes to entertain both views, ours of a heterogeneous catalysis within three phases of matter and the other of a homogeneous catalysis, it may be most comfortable to view our theoretic as furnishing a first more primitive stage for the development and the other as furnishing complementary detail.

Pre- and Retrodictive Testing for Life's Evolution

Clearly such a wide ranging speculation (or set of speculations) requires test. How do we test these ideas? We believe that there are two general types of tests. One is de novo. We believe that we can go into the laboratory and – as an R and D project no different from many others that people like ourselves have pursued in the past – produce life de novo by following the heterogeneous reactor bed clues that we have laid down in this paper. Estimable time scale for such a research project? In our betting view, perhaps three years. We believe this to be one such useful test. We have alluded to that possibility elsewhere and will pursue it no further here. That research depends on some one having sufficient funding and R and D background to pursue the research. (At the author's age, there is no longer any need to chase R and D funds. The project has to be for someone else). Another is to test the idea retrodictively on a sister planet whose early history may have resembled the Earth's. In particular, for this we will use and compare information from Earth and Mars for the test. In the remainder of this paper, we will attempt to assemble such information in preliminary fashion. We emphasize that our knowledge about Mars is minuscule. We make no claim to such knowledge. Instead we will assemble its story – for some such preliminary discussion – from one basic source, Carr (32).

Earth information about modeling early planetary events – Note that we used the Taylor story (2) to pass from 4.56 to 4.45 Gya. Now we would like to get to the production of volcanism, which we modelled as of 4.25 (± 0.05) Gya on Earth. Is there Earth evidence? Yes. Apparently the very earliest surface material known on Earth *from Earth* are zircons dated as of 4.2 Gya. The agreement is as good as could be fortuitously expected (More commonly, it is not expected that igneous material earlier than 3.9 Gya will ever be found. The more usual datings are of metamorphosed material such as Isua as of 3.8 Gya).

Long after that early epoch, we have the currently accepted notion of continents having assembled about 0.2 Gya (e.g., Pangaea, Gondwanaland), which commonly has been interpreted as in the following statement (Carr (32)): "Earth's surface is thus a complex system, in which material is being recycled both through the mantle, by subduction and ocean-floor spreading, and within the lithosphere and hydrosphere, by weathering, metamorphism, erosion, and deposition. There are reasons to believe that the entire system is in a crude equilibrium, because the composition of the main interfaces, the ocean, and the atmosphere appear to have remained approximately constant for the last billion years or so . . . . This is speculative, however. *Particularly uncertain are the rates of tectonic activity associated with plate motions prior to 200 million years ago, since the ocean record from before this time is almost nonexistent, and the continental record is fragmentary*" [our underlining].

In extension of those views, partially in contrast, we call attention to a NASA study that we did for their exobiology program in 1980–1981 (14), a study devoted to the thermodynamics of six interacting Earth systems (a program unfortunately aborted after only one year of contribution). In that one year of study, we were able to find, combine, and develop the following set of notions: (a) that Turcotte, Burke ((10) – 1978) had proposed a 0.3–0.6 Gy roll process in the Earth's mantle; (b) that Vail et al. ((12) – 1979) had established a uniform data base for the fluctuating component of Earth sea and continent level back to 0.55 Gya; (c) that the geophysicists (see, Wood (33) – 1980; Gass, Wright (34) – 1980) had established sea level regulation as a uniformitarian (regulated) process back to 2.5 Gya, namely that the Earth's surface material had been only substantially reworked after that data rather than added to; (d) that our 1960 study of the hydrology of large land masses (Iberall, Cardon (35); Iberall, (36)) had established a quantitative theory of continental erosion, in accord with (e) earlier results obtained by Elder (37) – 1976). In the latter case, we had independently shown and verified such prior work on the hydrological processes of physical and chemical erosion of continents. This cluster of conjectures thus had both theoretical and experimental support. Most telling was (f) the discovery that Russian research from the Asian landmass, e.g., Beloussov (clearly for an American audience was the invitation for Beloussov (11) to write the 1975 Encyclopaedia Brittanica article on "Continents, Development of"), had noted that with regard to tectonic cycles: "Precambrian metamorphism was preferentially confined to certain intervals of time. These time intervals [Gya] are . . . 3.0–2.8; 2.6–2.5; 2.2–2.0; 1.8–1.6; around 1.2; 1.0–0.9; and 0.6–0.5. These figures show that Precambrian metamorphism recurred at discrete intervals of [0.3 to 0.6 Gy]" (The actual approximate mean interval separation of the events, from these data is near 0.45 Gy). Thus our 1979 conjecture in (1) was not invented out of virgin cloth. We only had rediscovered the steps and were perhaps among many others who had attempted to unify the picture (which is what our 1980 study for NASA was about). In this light, this current attempt at modeling we regard to be an 'updating' of the earlier status of our model for both geophysical and biophysical picturing. In our opinion it vindicates the thrust or our earlier work of beginning an attempt to unify six thermodynamic models of Earth's processes, even if we were abruptly thrown out of the program and replaced by a more namecatching theme that is still pursued in name and which still seems quite lightweight.

As far as Mars is concerned, for further verification and vindication of our model, we will abstract our information from an acknowledged expert, Carr, and enter into dialogue with his excellent discussions. Before going on to the Mars question, we might ask – as a near final Earth question – what the oldest age is that has been discovered in the Russian Asian sequence. The clear answer is approximately 3.0 Gya, and if the question is asked why no earlier data, the clear nominal answer is that the material has been turned over, and that perhaps some day very deep samples might show earlier dates.

Mars information about a model of early planetary events – With regard to terrestrial volcanoes, Carr (32) points out that they are governed largely by plate motion. Volcanism is largely concentrated along the plate margins; the type of volcanism depends on the type of plate junction. For example, along midoceanic ridges volcanic activity is almost exclusively basaltic. The only exceptions are where major mountains form (e.g., in Iceland), where small amounts of more silicic magmas may also have erupted. Along subduction zones volcanism is more varied. Where a continental plate rides over a downgoing oceanic plate, the continental plate margin may exhibit zones. There are a few types of volcanic features that are difficult to relate to plate margins, though they may have been affected by plate motion. The Earth plate formation and Earth volcanism we outlined is consistent with such startup processes for the 4.45–4.25 Gya epoch on Earth.

On Mars, he points out in contrast, there is no evidence of plate motion, which we take to mean horizontal motion. Thus the arcuate chains of mountains that characterize terrestrial subduction zones are totally absent. Compressional features of any type are seldom found. Where layering is observed, it is almost always horizontal, with no indication of folding. Strike slip movement, occurring on Earth as a result of plates moving laterally with respect to one another, appears absent on Mars, despite the existence of many large cratered regions in which such movements could easily be detected. Thus it appears that the crust of Mars is stable and not broken into laterally moving plates like that of Earth.

The type of volcanism on Mars is correspondingly different. Volcanic cones, which typically occur along subduction zones on Earth, are relatively rare. Thus he points out that it is not unreasonable to assume that the andesite and alkali magmas that typify subduction zone volcanism are also rare. Such an assumption is consistent with the limited compositional data there exists for Mars, which suggests that most of the primary rocks are iron-rich and basic or ultrabasic. The most prominent volcanic features on Mars are shield volcanoes and flood basalts, both of which occur within plates on Earth and are difficult to relate to horizontal plate motion. The martian shield volcanoes, however, grow to much greater sizes than those on Earth, probably because of the greater stability and thickness of the martian crust. We would take this to mean that laterally moving plates are not the same as a solid skin which deflects in place. I thus take Carr's comments to mean that there is little evidence for any significant subduction motion on Mars, but – as we proposed for early Earth – a significant amount of 'rock-and-roll' motion of the skin in place, sufficient as on Earth to deform and crack the solid skin in places and permit volcanic activity.

Carr further points out that the history of volcanic activity on Mars is dominated by the formation of lava plains and large shield volcanoes. That history can be reconstructed reasonably well from the ages of craters on different volcanic features. The oldest recognizable volcanics are on the ridged plateau plains which cover about one third of the old cratered terrain. Flow fronts are rare on these plains, but their vast extent, smooth surface, and wrinkle ridges all suggest a volcanic origin. Most of the plateau plains are ancient, having perhaps 3,000 craters diametrally greater than 1 km per million sq km, which is as many as any other part of the planet except for the rough plateau areas of the densely cratered terrain. Despite an age that is probably earlier than 3.5 Gya, most of the craters on the ridged plains look quite fresh, indicating that they formed after the early era in which intense crater obliteration took place, and also after the early high cratering rates had declined. It is quite unlikely that the start of intense volcanism coincided with the decline in cratering and obliteration. More probably volcanic activity was near continuous, but volcanic regions can only be recognized as those that formed after the landscape had stabilized. Effectively thus all evidence of the volcanism that occurred before 3.9 Gya has been either lost or is unrecognizable.

We interpret these summarizing comments as being consistent with our 4.45–4.25 Gya Earth equivalent modeling for the appearance of a first generation of volcanic activity. An existence of early cratering is evidence of local plastic yield. Its obliteration is further continuing evidence of plastic yield but at a more extended field form. If it is unlikely that intense volcanism started with the decline in cratering and its obliteration, there must have been an epoch of plastic yielding to perform the obliteration without a rupturing that would permit volcanism. Thus such stress levels had to be later, and volcanism that occurred would have had to take place at that higher level of stress. Thus the sequence we see is formation of a surface skin even with bombardment, heat treatment back up nearly to the yield point for reformation, finally a cracking of the surface under a first generation of rolling and rocking of the surface so as to release volcanic flows, and then renewed bombardment, such processes having thus reached an Earth equivalent time of 4.2 Gya. If Mars were not driven any further, then its skin would have stayed in place horizontally, subject only to uplifting 'rocking', at which point internal 'lava' flows would begin to ooze from the cracked skin.

The plain skin regions whose extents are defined by volcanoes may have had starts before 3.9 Gya, but this is as close as the evidence that has been uncovered till now can get to our proposed 4.2 Gya. Thus the data are not inconsistent with our model. Apparently it is not possible yet to trace the earliest volcanic activity on Mars, due mostly to obliteration by long continuing bombardment and crater formation.

Thereafter, continuing from Carr, volcanic activity on Mars then became progressively more restricted with time. Between 2.5 and 4 Gya extensive volcanic activity resulted in the formation of most of the sparsely cratered plains of the northern hemisphere and the ridged plains of the densely cratered terrain. After 2.5 Gya, activity was largely restricted to around the Tharsis bulge and to some of the northern plains, while in the last billion years, volcanism occurred exclusivly near the crest and on the northwest flank of the bulge. This, to us, acknowledges that a date of perhaps 4.0 or earlier might have been associated with a beginning of extensive volcanic activity. In our view, this appears to be one more test of no inconsistency with our modeling; a conceptual gap is now possibly related to differences between 4.2 and 4.0 Gya.

The tectonic history of Mars, as Carr describes it, is vastly different from that of Earth. Deformation of Earth's crust is controlled by the constant motion of the surface plates with respect to one another. At subduction zones thick sedimentary sequences accumulate in linear troughs, then become squeezed, folded, and metamorphosed as they are caught between the converging plates. Enormous transcurrent fault zones develop where one plate slides by another, and rift zones form where plates diverge. The whole system is dynamic, with stresses in the lithosphere constantly changing as the configuration of the plates change. On the other hand, despite arguments that the equatorial canyons may be analogous to terrestrial midoceanic ridges, the surface of Mars appears to have been quite stable throughout its history. There are no linear depositional trenches, no mountain chains, few, if any, folded rock sequences, and no large transcurrent fault zones. Moreover, the stresses within the crust appear to have maintained one configuration for billions of years, in striking contrast to the continuously shifting configurations of Earth.

In that sharp contrast, the tectonics of Mars surface are dominated by the one major feature, the Tharsis bulge. Away from the bulge deformation features are rare, and in fact almost all other deformation features appear to be related to Tharsis.

That bulge has clearly played a major role in the evolution of Mars' surface. Radial fractures around the rise affect almost an entire hemisphere, and wrinkle ridges which resemble those on the lunar maria, occur around much of the bulge. The largest and youngest volcanoes are on its flanks, as is the vast system of equatorial canyons. The bulge is so large that its formation may have affected precession of the planet's rotation axis, thereby also affecting climate. It has even influenced surface processes by perturbing the wind regime and possibly also controlling migration of groundwater.

The bulge is of interest not only for its effects on surface geology but also for the clues it provides concerning the nature of the planet's interior. Coincident with the bulge is a large gravity anomaly, which provides a means of assessing the structure of the crust and the density distribution down to depths of several hundred kilometers. The anomaly, in addition, gives some indication as to whether the bulge is being actively supported from below, such as by convection, or whether it is supported passively by the strength of the crust. Somewhat less definitively the bulge provides clues concerning events that took place early in the history of the planet, since formation of the rise must have been related in some way to dynamical and chemical anisotropies, such as might be associated with mantle convection, core formation, or an uneven distribution of radioactive elements. Physical consideration of the Tharsis bulge thus touch on some of the broadest issues concerning the evolution of the planet.

Several attempts have been made to explain faulting around the bulge and the broad outlines of the deformational history are relatively clear, states Carr.

Clearly Mars effectively has had no lateral or horizontal movement of its surface skin. On Earth, our model dated such events as beginning at 4.0 or perhaps in the 4.0–3.9 epoch. Thus Mars' history is consistent with the dynamic state of earlier processes involving no lateral movement. So the question moves up to the evidence for strong and early cracking, volcanism, and rocking. This apparently has to be related, for a main view of Mars, to the Tharsis bulge, its surrounding volcanism, and its deformations and cracking and ridges (e.g., one big bulge, instead of many plates). While many of its processes are young, the earliest dates in (32) are: "Within Tharsis volcanic plains date from in excess of 3 [Gya] . . .": or, referring to cratered regions south of the Tharsis bulge, "The old cratered terrain may have been uplifted to form the bulge. . . . Alternatively, no uplift occurred, but volcanoes started accumulating on the bulge before the decline in the cratering rate 3.9 [Gya]"; and "The period of most intense fracturing postdates the surface of Lunae Planum [east of Tharsis] and features of equivalent age. . . . [C]raters . . . suggest ages in the 2.5–3.5 [Gy] range. . . . The fracturing thus appears to have tapered off rapidly after the deposition of the cratered plains . . . the falloff probably occurred over 2.5 [Gya]." Our model visualized Earth equivalent deformative rock and rolling, cracking, and volcanism beginning in the 4.25–4.2 era, or at most in the 4.25–4.1 era. With more extensive processes frozen out or not appearing on Mars in the 4.0–3.9 epoch, we would not be surprised to find a beginning of skin rock and rolling, cracking, and volcanism nearly in those epochs, and continuing in moderate form for an appreciable time, whereas on Earth the process continued, driven, to more extensive horizontal movements. Thus our thesis of rocking-in-place, some skin cracking, volcanism and their dating for Earth and Mars remains reasonably consistent.

Carr indicates that fracturing continued after this time of 2.5 Gya, but with considerably less intensity, e.g. in our model, continued rocking. The simplest explanation for fracturing among lava flows is that volcanic activity and faulting took place simultaneously, which is also compatible with our model. His general picture, therefore, is that the deformation took place mostly in the first half of the planet's history but continued to the present at a low level, which in our opinion is compatible with the first type of surface skin rocking, frozen dynamically on Mars so that the plate motion and volcanism process gradually decayed, whereas on Earth the vigorous roll drive, itself driven by augmenting nuclear heating, drove the plates into both horizontal and vertical movements and was responsible for the continued, e.g. perhaps 7 or so, shiftings in the horizontal plate groupings that make up Beloussov's record.

Although the general region of Tharsis remained at the center of the fracture system, the precise location of the center may have shifted slightly on occasion. After what had to be an early intense episode, faulting continued about the same center at a relatively low level up to the present time. However, its continued fracturing is caused by the presence of the topographic and gravity high and not by the process of its initial formation.

As a summary and statement of conclusions about Mars, Carr points out that the presence of the large bulge in the Tharsis region and, to a much lesser extent, around Elysium, created stresses in the crust and, as a result, an extensive array of radial fractures. The ordering relations of superposition suggest that most of the fractures are old, having formed in the first half of the planet's history, but that fracturing continued into essentially recent times, as indicated by the finding of an occasional radial fracture cutting a young lava flow. Canyons appear to have been caused largely by faulting along the radial fractures, although other processes, such as landsliding, gullying, and undermining, have contributed to their present configuration. Nevertheless the canyons may be quite ancient features that have continued to form throughout geologic time as a consequence of the stress pattern initially established by the Tharsis bulge.

With regard to the water system that has existed on Mars, much of the water that cut the runoff channels early in the planet's history and some that outgassed later during subsequent volcanism may have become part of a vast artesian system trapped below the thick permafrost that developed after the atmosphere became thinned. Slow percolation probably resulted in the accumulation of water in low areas, such as around the Chryse basin, leading to periodic breakouts which formed the large outflow channels. Although most such channels appear to be relatively old, they are younger than the runoff channels and they may have continued to form episodically until relatively late times. What happened to the water that cut these channels is uncertain. It could not have returned to the groundwater system because of the permafrost seal. More probably the water exists as ice, possibly interbedded with volcanic and eolian debris in the high latitudes.

Mars, not different from other planets, is subject to periodic changes in climate as a result of precession of its orbital and rotational axes and variations in eccentricity and obliquity of those motions. Such changes have to affect the general circulation of the atmosphere and the stability of volatiles at the surface and may cause variations in atmospheric pressure as a result of adsorption and desorption of CO_2 in the regolith. Key evidence for such climate changes is best preserved at Mars' poles, although the changes may also be a prime cause of the complex erosional and depositional histories experienced by all of its surfaces at high latitudes. There are sequences of layered sediments of geologically recent age at both poles as may be judged from the almost total lack of superposed craters. The sediments are believed to consist largely of eolian debris, possibly mixed with ice, and the layering may be the result of variable rates of accumulation induced by climate changes.

Thus one may note that in some ways Mars' history resembles Earth's. It has had an atmosphere, although now much thinner than Earth's, and it has a surface that had been modified by the wind to produce a variety of erosional depositional landforms. There is considerable evidence of nearsurface water, whether as ice or liquid. The water appears to have eroded parts of the surface and reacted with the surface materials to produce weathered products. The surface of Mars also provides abundant evidence of deformation and volcanism, and both seem to have continued into the relatively recent geologic past. *Like Earth's surface the martian surface has been subject to chemical reaction with the atmosphere, erosion by wind and water, and modification by extensive volcanism.* But the extent of large atmospheric interactions on Mars likely had to be restricted to a rather brief and early epoch. Despite similarities, the differences between the two planets are very great.

Another major cause of the differences between the two planets is the contrast in their tectonics. Earth's surface geology is dominated by the effects of plate motion. Interaction between the plates controls the appearance and distribution of continents, the formation of mountain chains, the location of volcanic tectonic activity, and the general style of crustal deformation. Indeed there are few surface geologic processes that are not affected in some way by plate tectonics. New lithosphere forms continually where plates diverge at mid-oceanic ridges, and old lithosphere is ingested at subduction zones, where one plate dips under another. Since it is normally the oceanic lithosphere that is subducted, most of the ocean floor is relatively young, very little being older than 200 million years. Only on the continents, at a few places, is there any record of events that took place billions of years ago. In contrast Mars' crust is fixed in its time sequence, and all those features, such as linear mountain chains, transcurrent fault zones, and linear ocean deeps, that on Earth characterize interaction between the plates, are absent. Such stability results in preservation of an ancient record in almost all areas of Mars' surface.

This summary report, thus far, seems to us to be consistent with the processes that preceded to plate cracking, rocking, and volcanism on Mars, but was then frozen out; while continuing on Earth.

Continuing the summary, another basic difference between the surfaces of Earth and Mars is the continued presence of abundant water in liquid form on Earth. Water plays an essential role in two major processes: first, as weathering – the chemical breakdown of rock-forming minerals, mainly by hydration and carbonation, into mineral assemblages more in equilibrium with conditions at the surface – and second, as gradation – the steady reduction of surface relief by erosion and transport of material from high to low areas. Both processes are complemented by additional opposing processes, such as metamorphism, in which the low-temperature weathered products are reconstituted into high-temperature assemblages, and also by tectonic activity, which tend to accentuate surface relief. Primary igneous rock minerals, for example, are altered during weathering into clays and other minerals, which are then carried to the oceans and deposited in sedimentary basins, such as the troughs along subduction zones. Deep burial of this material can result in melting, to form other igneous rocks, or in metamorphism and formation of new high-temperature assemblages. Uplift may then reexpose the materials to weathering and the cycle can repeat. Gradation is an essential part of this hydrological cycle, in that the weathered products must be eroded and carried to the oceans if they are to be deeply buried and metamorphosed. Wind may participate, but most erosion and transport is by running water involved in a hydrological cycle acting upon exposed plates.

As we pointed out earlier in this paper, thereby acting as our introduction to Carr's comments on how Earth's processes make up a complex system, we have accounted for those processes of continued erosion of continents, which – by their appearance as horizontal reformations in accord with the data of Russian geologists – make up a geological column in accord with such geological data, geophysical modeling, and the sea level fluctuations of the past 2.5 Gy. Thus horizontal motion, extensive hydrological and meteorologically promoted erosion of both physical and chemical nature proceeded. There is little speculative in the broad outlines.

Carr points out in his summary that, in contrast, the dynamics of the martian crust are totally different. Although the planet has been volcanically and tectonically active throughout much of its history, the lithosphere appears not to have been recycled through the underlying asthenosphere. Huge volcanoes have formed, as well as vast fracture systems, but the activity is not concentrated in linear zones as on Earth. Instead it affects areas of broad regional extent. Furthermore, although water has probably flowed across the martian surface at times in its early history, and possibly intermittently subsequently, river erosion has been trivial. Where channels are present, they mostly meander between the craters or down the crater rims. Rarely has erosion been sufficiently sustained to wear away the craters themselves. Erosion of young features, such as the large volcanoes, is imperceptible.

Comparable with our views, on Earth uplift is followed by enhanced erosion and by downwarping by rapid sedimentation, so that a rough equilibrium is maintained between the relief-forming processes and gradation by running water. On Mars, because of the limited fluvial erosion and deposition, no such equilibrium is achieved. If relief is created, such as by volcanic, tectonic, or impact processes, it largely remains. If any equilibrium is achieved, it is not with the surficial processes of erosion and deposition, but rather with the ability of the lithosphere to sustain the loads created by the relief. As a consequence Mars, despite its smaller size, has considerably more relief. Volcanoes have grown to almost three times the height of Mt. Everest, canyons several kilometers deep have survived for billions of years, and a broad 10-km-high upwarp of continental dimensions has apparently persisted in the region of Tharsis for much of the planet's history.

The lack of significant sediment transport implies, further, that weathering products are not recycled. Chemical analyses of the surface materials indicate that weathered products, such as clays and evaporites, are present. It is not clear how or where these form, but water may be abundant below the surface as ice or as liquid within artesian reservoirs, and such water is likely to be an efficient weathering agent, probably being charged with carbon dioxide. Thus, where subsurface rocks are in contact with groundwater, weathering may occur, but without erosion and removal of the weathering products alteration must be slowed, as a protective thin cover of weathered material accumulates around the unaltered rocks. The subsurface rocks may therefore be in a state of static equilibrium with the hydrosphere and atmosphere, in contrast to the apparant dynamic interaction that occurs on Earth. Although it may be an overgeneralization; nevertheless the rate of interaction on Mars appears to be orders of magnitude lower than that on Earth.

Thus in addition to the lack of cycling of the martian lithosphere through the upper mantle, caused by the absence of plate tectonics, the cycling of the surface materials and the interaction with the hydrosphere and atmosphere are hindered by climatic conditions that prevent flow of water across the surface. The result is an active planet with enormous surface relief, on which features with a wide range of ages are preserved in almost pristine condition.

As a characterization of the dialectic between a detailed expert point of view and a generalist's physical point of view, I seem to see reasonable conformity. I read the summary to mean that the freezing out roll and rock system, while getting weaker, was strong enough to produce appreciable early volcanism while also becoming weaker; that water pooling was significant but not of sufficient amount nor warmed enough to produce much of an atmosphere, so that no powerful sequence of erosion cycles ever existed. The water system was juvenile. Namely the basically braided river systems represented flows much less than Earth's runoff of about 8 inches of water per year. We might guess that it looked more like 2 inches of water runoff or less. Thus we would not believe that one could expect to find the kind of terminal chemical erosion schema that exists on Earth wherein the same ion exchange ingredients and concentrations (except for NaCl) are found draining from all continental sized river systems. The relative strengths of the interacting force systems, although similar, are briefly different.

Some model reassessment from inner planet bombardment – The advantage of having done this comparative view of the two planets is to indicate to us that we erred in our model by having left out consideration of the process of material bombardment. Thus we will review our modeling again but will consider the effects of bombardment and also attend to its role in providing a common scale for interplanetary events. We will confine our review to meteorite showers, their history, and the effects on the Moon, Mars, and Earth.

4.56 Gya – The initial history for these three planetary bodies was the same, so that this time scale was marked by an intense influx of matter accretion. A good demonstration of this can be taken from (3). Therein, in Table 2, p. 286, one finds an extensive table of the oldest meteorites. These average about 4.55 Gya with a standard deviation of about ± 0.05 Gy. We thus have a sharp common date for all three bodies.

4.45 Gya – As we have indicated, the evidence seems fairly convincing that an appreciable segregation and accretion had taken place of these three bodies ((3), p. 304; p. 309 – age of the Moon 4.5–4.6, initial differentiation of the crust between 4.3 and 4.6, after remelting of a thin shell; highland rocks out to 4.5; Earth's origin between 4.45 and 4.55, p. 318; Moon accreted 4.5–4.6, a first igneous event of crystallization took place, also the Earth accreted, p. 601; lunar events from 4.4 are well documented, p. 642, lunar basalts crystallize with a clustering age of about 4.4 Gya).

4.3 Gya – An intense bombardment up through asteroid size took place. On the Moon this must have caused sufficient plastic flow of the surface to have oblitered surface features. One finds the highland breccias to have been so formed after 4.3 ((3), p. 309). On Mars there is also an early obliteration of craters ((32), p. 58). When? Before 4.0 ((32), p. 56, 59, 60). [We begin to interpret this sequence in the following way. The early 4.56 bombardment was part of the initial ingathering – of both matter and energy. The formative planetary process, e.g., to 4.45, then took place. The Moon, as the smallest of these inner planetary bodies, formed a skin, then was reheated and reworked on the surface during periods of intense bombardment, e.g., 4.3. Mars, 8 times larger in volume, also crusted in the interim, 4.45–4.3; cracked its skin under stresses, presumably internally generated (rolls?; other asymmetric force systems?); exhibited some rock and roll of its skin surface; precipitated an early moderate hydrology and meteorology; created very early runoff channels with some erosion. Its surface was also reworked during the 4.3 bombardment; its early craters, involving some volcanics, obliterated; a second generation of hydrological and meteorological processes created the final fluvial channel system. On Earth, 8 times larger in volume than Mars, a skin also crusted in the 4.45–4.25 period; it developed an intense internal roll system, which kept differentiating its internal and surface material; it exhibited rock and roll; it also exhibited considerable volcanic action; it began an intense meteorological system (e.g., like Venus?) and a juvenile hydrological system; it had its surface considerably reworked at 4.3, which thereby continued Earth's surface redifferentiation process.

Thus the main contribution of the 4.3 Gya bombardment was to obliterate early surface features on these inner planets and their satellites, add to surface differentiation and to material accretion; add some heat energy to those bodies, thus prolonging their effective startup period.

4.05 Gya – Some interim observations, nominally before another period of intense bombardment (e.g., at 4.0 Gya), are as follows: on Mars, continuing evidence for no horizontal plate movement ((32), p. 204); no recycling of its crust ((32), p. 205); appreciable solid surface strain of one or more surface plates ((32), p. 122; the Tharsis bulge). On Earth, in some qualified sense, its differentiation of surface and core was largely completed by this time (e.g., (3), p. 335, 461, 320, 318).

4.0 Gya – There was an intense bombardment of these inner planets. On the Moon, this was responsible for its high cratering rate at 4.0, declining rapidly at 3.9 ((32), p. 56; (3), p. 312). On Mars, cratering is more dense before and up to 3.9, sparse after 3.9 ((32), p. 62, 65). This does not mean that there was not any earlier obliterated cratering on the Moon, only that a last intense phase took place at 4.0 Gya. There were fewer large impacts on Mars as compared to the Moon. [The impression is left that Mars cratering melted more to lose more of its surface sharpness than the Moon; while on Earth there are almost no cratering remnants. Such diminishing shear strength is compatible with increasing surface plasticity in the sequence from Moon to Mars to Earth].

3.9 Gya – Apparently bombardment diminished drastically, virtually ceased, in the interval 3.9–3.8 Gya. On the Moon, cratering declined rapidly by 3.9. On Mars, drastic decline of impact rates at 3.9; but with volcanism all over ((32), p. 203, 62). Mars exhibited runoff and an appreciable atmosphere up to about 3.9 ((32), p. 203). It also exhibits volcanic craters from recent ages to about 3.9 (more or less uniformly – (32), p. 94). Ridged plain craters older than 3.5, are fresh, likely later than 3.9 ((32), p. 112). On Earth, it is unlikely to find crustal rocks older than 3.9. This is the time required from startup to differentiate into core, mantle, crust by heating of isotopes ((3), p. 321).

Modeling that very strongly supports the picture of Mars' juvenile fluvial processes has recently been furnished by Melosh and Vickery (41). They infer, from modeling the impact erosion of its primordial atmosphere, that Mars initially had an atmosphere of about 1 bar, competent to support liquid flow on its surface and an early hydrological cycle. That erosion of atmosphere, because of Mars' size, was effectively complete by about 3.9 Gya, earlier than the end of the heavy bombardment era. Earth and Venus, because of larger size, suffered negligible such erosion.

3.8 Gya – Resummarizing Moon's history to 3.8 Gya: fast accretion; fast cooling; remelting of skin from bombardment; oldest rocks under the magma erupted to form the mare basalts. "This period of mare volcanism overlapped the period of intense bombardment of the moon which began with the final stages of accretion ($\approx$ 4.3) and ceased $\approx$ 3.8" (3). On Mars, its atmosphere was lost after 3.9. Its fluvial erosion was not sustained, it was trivial ((32), p. 203, 205). Oldest rocks, supercrustal, gneisses, 3.8 – Isua ((3), p. 320). Thus we can say that there was a second less intense bombardment at 4.0, which virtually ceased by 3.8–3.9. The Moon, after that date, is effectively a cold body. Mars exhibits some plastic yielding (rock and roll), and some weak continuing volcanism. Mars, thus, with processes more or less frozen out like those of Earth's in the 4.0–4.1 epoch, exhibits some of the primitive fluvial processes of Earth.

Life, Retrodictive, from Mars

We take on the issue of using a second generation of Mars exploration for life in the following sense: In an earlier NASA program that we participated in, Morowitz ((26), following Sagan, see Fox, (25)) contributed to two major ideas – if life had to develop around a relatively narrow range thermodynamic engine source and sink, a photosynthetic energy pump was a most likely source, and this likely limited the star types which might act as a source of energy to main sequence stellar classes very like our sun (energy in the visual). We regard this as a marvellous guess, but with more modern consideration what is now suggestive is a number of possible short range chemical reactions, e.g., iron, sulfur, methane, manganese, but still including the feasibility of visual organic dyes acting as energy pumps. Even more so than any earlier surmise, the bonding competence of carbon seems most likely and compelling. Our own surmise also includes the salient significance of silicic materials, metallo-organic materials, hydrocarbons and water. Morowitz (see, (18, 26, 38)), then, quite usefully, has always stressed looking at the process as chemistry being built up from elementary compounds and has sought to narrow and pursue that line thermodynamically. We, in contrast, have explored whole organism processes and have looked more from the point of view of irreversible thermodynamic cyclic engine processes, stressing always their hydrodynamic aspects (38). Looked at too extremely, one might never expect these two views to meet. However, a more relaxed view of these two poles easily suggests that they will both be right. That is we continue to stress the form of the dynamic reactor and reaction bed in field form; Morowitz continues to stress the stoichiometry of the reactions whose feasibility has to be discovered.

A first round of exploration on Mars, as a test bed to learn something about life's feasible reactions, drew somewhat of a blank. Our prediction, based on what we understood at the time, was only that one might find a relatively complex chemistry, but with no idea whether this might reach up to process levels at all interesting for life. To a certain extent, that is what we believe the message from those earlier experiments was. Our current view is as follows: We now believe, from the analysis that we have given, that fossil life will not be found on Mars, but something else can be discovered which is scientifically more important. If the suggestions we have made that Mars exhibits the frozen-in-time processes of Earth as of 4.2–4.1 Gya have any merit, then we believe that one ought to be able to find the chemistry landmark or landmarks that tell us what was the perferred or selective process on the way to life. This is more important than finding fossil life on Mars. If fossils were found near their temporal origins (as they would have to be), we wouldn't know how it started; we would only have a continued recomfirmation for more SETI research (since SETI doesn't need confirmation, only continuing black-white or grey publicity). We feel that there is more to confirm in the force of Morowitz' conjectures: for example his conjecture regarding the Strecker reaction as being a significant pathway to biochemistry (18). More important is whether exploration of Mars' fluvial regions, if locked up in the 4.2–4.1 Gya Earth equivalent time, can exhibit positive chemical landmarks on the way to life in that chemical horserace: e.g., evidence of organic, metallo-organic compounds, iron, manganese, sulfur, visual dies, clay gels, or other dark horses. Of course, as a biased parent, I am willing to bet on the nose of my daughter's conjecture ((23) and forthcoming (39)) that it is iron, i.e., iron as the energy transformer on the way to iron bacteria. More safely, I might bet on iron to place or show rather than to win but my astrologer says . . . [he also notes that there is lots of iron on Mars!].

Summary

Thus in summary of the notions that permit me to retrodict required pre-life properties to be examined for on Mars:

1. There is a space-time self-scaling in sedimentary beds through which water has trickled (a range as extensive as seconds to millions of years; from fractional micrometers to boulders).
2. One requires three matter state interfaces with fluctuating process and time scales within sedimentary beds for life to start de novo.
3. One needs slow water flow fluctuating in the sedimentary beds.
4. One needs the presence of small quantities of hydrocarbons in these beds (small quantities only are required so that they may self-scale as a thin coating).
5. Such conditions can produce self-scaled micelles.
6. In a porous medium of clay, such streams can also appreciably self scale and produce fingering, evidence of weakened surface tension forces.
7. A metallo-organic compound or complex is needed that can pass into these cells because of its oil-water differential solubility.
8. Such a material, if is can pass in easily enough and if it has a moderate energy state transition, such as iron, can act as a thermodynamic pumping engine for osmosis – the governing of a two stream differential flow.
9. If one of those two streams is an early appearance of an inbearing water stream into micelles, then the system process of grow-divide may take place within the bed, with a continuing growth outward of these cells. The process which we visualize, thus far, is a continued growth of a frothing-like material that appears within sedimentary beds that can grow outward with its one step engine process.
10. There is the assumption that division will take place as a stability transition at some critical concentration, so that the frothing growth is favorably enhanced. In this depiction, the oily compound, the water, and the metallo-organic will scale the process. This has required no genetic coding material except the metallo-organic. In order to operate, it need only develop a segment length of the 'membrane' thickness, i.e., 100 Å or so; it does not need to have a catalytic ball consisting of perhaps a million lengths of that size.
11. We can imagine any number of different 'metals' attaching to the organic so that winning (acquiring selective advantage in governing the dominant reaction rate of producing number to dominate the region) becomes a matter of a race. In time, thus, we can then imagine any of the components to become advantaged, namely what will become recognized as possessing selective chemical advantage. In general by this we will mean a speeding up of some physical or chemical process so that it becomes more dominant. For example, we can imagine extended transformation in the metallo-organic so as to be able to pump more energy, or to be able to speed up the division process, or to exhibit more control of its reaction growth. We require only very modest polymeric properties in its early forms.
12. Thus our basic prediction is that on Mars you may find metallo-organic compounds that will illustrate the kind of material that is the one that wins in the race to life. And, of course, we bet on iron.

References

1) Iberall, A.; Soodak, H.: A physics for complex systems. In: Yates, F. (ed.), Self-organizing systems, pp. 429–430. Plenum Press, NY 1987.

2) Taylor, S.: The origin of the moon. Amer. Sci. 75, 468–477 (1987)

3) Dermott, S.: The origin of the solar system. Wiley, NY 1978.

4) Robertson, E.; Hays, J.; Knopoff, L.: The nature of the solid earth. McGraw-Hill, NY 1972

5) Windley, B. (ed.): The early history of the earth. Wiley, NY 1976.

6) Smith, J.: The first 800 million years of earth's history. Philos. Trans. R. Soc. London, A. 301, 401–422 (1982)

7) Stewart, G.: A violent birth for Mercury. Nature 335, 496–497 (1988)

8) Newsom, H.; Taylor, S.: Geochemical implications of the formation of the Moon by a single giant impact. Nature 338, 29–34 (1989)

9) Hart, M.: The evolution of the atmosphere of the earth. Icarus 33, 23–39 (1978)

Habitable zones about main-sequence stars. Icarus 37, 251–257 (1979)

Was the pre-biotic atmosphere of the earth heavily reducing? Origins of Life 9, 261–266 (1979)

10) Turcotte, D.; Burke, K.: Global sea-level changes and the thermal structure of the earth. Earth Plan. Sci. Lett. 41, 341–346 (1978)

11) Beloussov, V. Continents, development of. Encyc. Brittanica, 5, 119–123 (1975)

12) Vail, P. et al.: Seismic stratigraphy and global changes of sea level. AAPG Memoir 26, 49–212 (1977); Vail, P.; Mitchum, R.: Global cycles of relative cycles of sea level from seismic stratigraphy. AAPG Memoir 29, 467–472 (1979)

13) Iberall, A.: Possible Correlation between Species Extinction, Evolution and Plate Adjustments to Continental Erosion. GeoJournal 16.2, 229–232 (1988)

14) Iberall, A.; Cardon, S.: Contributions to a thermodynamics of earth systems. NASA Contractors Reports, Contract NASW-3378, prepared by Gen. Tech. Serv. Inc., May, Aug., Nov. 1980, Jan. 1981 for NASA-Washington.

15) Yates, F.: Self-organizing systems. Plenum Press, NY 1987.

16) Brock, T.: Precambrian evolution. Nature 288, 214–215 (1980)

17) Soodak, H.; Iberall, A.: Osmosis, diffusion, convection. Am. J. Physiol. 235, R3-R17 (1978); Forum on osmosis. IV. More on osmosis and diffusion. Am. J. Physiol. 237, R114–R122 (1979)

18) Morowitz, H.: A hardware view of biological organization. In: Yates, F. (ed.), Self-organizing systems, pp. 53–64. Plenum Press, NY 1987.

19) Orgel, L.: The origin of self-replicating molecules. In: Yates, F. (ed.), Self-organizing systems, pp. 65–74. Plenum Press, NY 1987.

Orgel, L.: Molecular replication and the origins of life. In: de Boer, J.; Dal, E.; Ulfbeck, O. (eds.) The lesson of quantum theory, 283–294. Elsevier, NY 1987.

20) Katchalsky, A.: Chemo-diffusional coupling in heterogeneous peptide synthesis. In: Oster, G.; Silver, I.; Tobias, C. (eds.). Irreversible thermodynamics and the origin of life, pp. 1–10. Gordon and Breach, NY 1974.

21) Pflug, H.: Yeast-like microfossils detected in oldest sediments of Earth. Naturwissenschaften 63, 611–615 (1978).

22) Appel, P.: On the Early Archaean Isua Iron-Formation, West Greenland. Precambrian Res. 11, 73–87 (1980)

23) Robbins, E.: *Appelalla ferrifera,* a possible new iron-coated microfossil in the Isua Iron-Formation, southwestern Greenland. In: Appel, P.; LaBerge, G. (eds.), pp. 141–154. Theophrastus, Athens 1987.

24) Schidlowski, M.: A 3,800 million year isotopic record of life from carbon in sedimentary rocks. Nature 333, 313–318 (1988)

25) Fox, S. (ed.): The origins of prebiological systems and of their molecular matrices. Academic Press, NY 1965.

Fox, S.; Dose, K.: Molecular evolution and the origin of life. Marcel Dekker, NY 1977.

26) Morowitz, H.: Energy flow in biology. Academic Press, NY 1968.

27) Wong, P.-z.: Fractal surfaces in porous media. In: Banavar, J.; Koplik, J.; Winkler, K. (eds.): AIP Conference Proceedings 154. Physics and chemistry of porous media II, pp. 304–318, Am. Inst. Phys. NY 1987.

28) Scheidegger, A.: The physics of flow through porous media. Univ. Toronto Press, Toronto 1974.

29) Iberall, A.; Schindler, A.: A kinetic theory, near-continuum model for membrane transport. Ann. Biomed. Engin. 1, 489–497 (1973)

30) Iberall, A.: A proposal for a force essential to biological organization. Perspect. Bio. Med. 18, 399–404 (1975)

31) Schuster, P.; Sigmund, K.: Self-organization of macromolecules. In: Yates, F. Self-organizing systems. pp. 75–111. Plenum Press, NY 1987.

Schuster, P.: The interface between chemistry and biology – laws determining regularities in early evolution. In: Pifat-Mrzljak, G. (ed.): Supramoleculular structure and function. pp. 154–185. Springer-Verlag, Berlin 1986.

32) Carr, M.: The surface of Mars. Yale Univ. Press, New Haven 1981.

33) Wood, R.: The fight between land and sea. New Sci. 87, 217–218 (1980)

34) Gass, I.; Wright, J.: Continents old and new. Nature 284, 217–218 (1980)

35) Iberall, A.; Cardon, S.; Schneider, H.: A study for the physical descrition of the hydrology of a larger land mass pertinent to water supply and pollution control. Four quarterly reports for DWSPC, Public Health Service, Dept. Health, Education, and Welfare, Washington, DC, Contract SAph 78640 (division currently in the Dept. of the Interior), 1961–1962.

36) Iberall, A.: On rivers. In: Yates, F. Self-organizing systems, pp. 33–48. Plenum Press, NY 1987.

37) Elder, J.: The bowels of the earth. Oxford U. Press, London 1976.

38) Morowitz, H.; Iberall, A.: Discussion sections. In: Yates, F.; Urquhart, J. (eds.), Temporal aspects of therapeutics, pp. 5–16, 17–29, 32–34, Plenum Press, NY 1973.

39) Robbins, E.; Iberall, A.: Microbial minerals of iron oxides in the earliest rocks on Earth: Evidence for life at 3,800 Myr and implications for the search for early life on Mars. In preparation.

40) Watson, J.; Hopkins, N.; Roberts, J.; Steitz, J.; Weiner, A.: Molecular Biology of the Gene, Vol. 2. Benjamin/Cummings Publ. Co. Inc. Menlo Park, CA., 4th Ed., 1987.

41) Melosh, H.; Vickery, A.: Impact erosion of the primordial atmosphere of Mars. Nature 338, 487–489 (1989)