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From meteorites to evolution and habitability of planets

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ABSTRACT

The evolution of planets is driven by the composition, structure, and thermal state of their internal core, mantle, lithosphere, and crust, and by interactions with a possible ocean and/or atmosphere. A planet's history is a long chronology of events with possibly a sequence of apocalyptic events in which asteroids, comets and their meteorite offspring play an important role. Large meteorite impacts on the young Earth could have contributed to the conditions for life to appear, and similarly large meteorite impacts could also create the conditions to erase life or drastically decrease biodiversity on the surface of the planet. Meteorites also contain valuable information to understand the evolution of a planet through their gas inclusion, their composition, and their cosmogenic isotopes. This paper addresses the evolution of the terrestrial bodies of our Solar System, in particular through all phenomena related to meteorites and what we can learn from them. This includes our present understanding of planet formation, their interior, their atmosphere, and the effects and relations of meteorites with respect to these reservoirs. It brings further insight into the origin and sustainability of life on planets, including Earth. Particular attention is devoted to Earth and Mars, as well as to planets and satellites possessing an atmosphere (Earth, Mars, Venus, and Titan) or a subsurface ocean (e.g., Europa), because those are the best candidates for hosting life. Though the conditions on the planets Earth, Mars, and Venus were probably similar soon after their formation, their histories have diverged about 4 billion years ago. The search for traces of life on early Earth serves as a case study to refine techniques/environments allowing the detection of potential habitats and possible life on other planets. A strong emphasis is placed on impact processes, an obvious shaper of planetary evolution, and on meteorites that document early Solar System evolution and witness the geological processes taking place on other planetary bodies.

1. Introduction

An unambiguous definition of life is currently lacking (Tsokolov, 2010), but one generally considers that life includes properties such as consuming nutrients and producing waste, the ability to reproduce and grow, pass on genetic information, evolve, and adapt to the varying conditions on a planet (Sagan, 1970). Terrestrial life requires *liquid water*. The stability of liquid water at the surface of a planet defines a habitable zone (HZ) around a star. In the Solar System, it stretches between Venus and Mars, but excludes these two planets. If the greenhouse effect is taken into account, the habitable zone may have included early Mars while the case for Venus is still debated. This definition neglects other important requirements for life such as a supply of *chemical elements* (C, H, O, N, P, S, and trace elements) and an *energy* source to drive biochemical reactions. Also, liquid water may exist in oceans covered by ice shells for example in the icy satellites of Jupiter (Schubert et al., 2004), which are located well outside the conventional habitable zone of the Solar System. Important geodynamic processes affect the habitability conditions of a planet and modify the planetary surface, the possibility to have liquid water, the thermal state, the energy budget and the availability of nutrients. Shortly after its formation at 4.56 Ga (Hadean 4.56–4.0 Ga (billion years)), evidence supports the presence of a liquid ocean and continental crust on Earth (Wilde et al., 2001). Earth may thus have been habitable very early on (Strasdeit, 2010). The origin of life is not understood yet but the

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oldest putative traces of life occur in the early Archaean ($\sim$3.5 Ga). Studies of early Earth habitats documented in rock containing traces of fossil life provide information about environmental conditions suitable for life beyond Earth, as well as methodologies for their identification and analyses. The extreme values of environmental conditions in which life thrives today can also be used to characterize the "envelope" of the existence of life and the range of potential extraterrestrial habitats. The requirement of nutrients for biosynthesis, growth, and reproduction suggest that a tectonically active planet with liquid water is required to replenish nutrients and sustain life (as currently known). These *dynamic processes* play a key role in the apparition and persistence of life.

In the frame of this paper, we envisage these statements and pay particular attention to what can be learned from the meteorites. Meteorites are the left over building blocks of the Solar System. As such they provide valuable clues to its origin and evolution as well as to the formation of the planets. The majority comes from the asteroid belt between Mars and Jupiter. Extremely rare ones were ejected from the deep crust of the Moon and Mars during large impact events. The meteorites are classified in groups corresponding to different evolution phases of the Solar Nebula. The most primitive, the carbonaceous chondrites, together with the other chondrites, originated from the break-up of small-size undifferentiated planetary bodies. Some carbonaceous chondrites have almost the same chemical composition as the Sun and resulted from the condensation of the solar nebula almost without any fractionation. Carbonaceous chondrites also contain complex organic compounds (e.g., amino acids) and may contribute to the understanding of the origin of life on Earth and to the ubiquity of organic chemistry. The other groups of meteorites (iron, stony-iron, and achondrites) originate from more evolved planetary bodies that have undergone several episodes of differentiation comparable to the formation of the core, mantle and crust on Earth, as well as episode(s) of shock metamorphism during planetary collisions. The value of meteorites to document astronomical, solar system and terrestrial processes does not have to be further demonstrated. They have provided, and continue to provide, data on stellar evolution and nucleosynthesis, the chronology of the solar system, the formation of planets, cosmic ray bombardment, the deep crust of Mars and the Moon, and so on.

In 1970 less than about 2000 meteorites had been recovered all over the entire land surface of the Earth. In the last 40 years, the samples collected in Antarctica have largely increased the world's collection of meteorites. The ice fields of Antarctica concentrate meteorites, including rare and precious ones. This concentration occurs when the flowing ice is stopped or slowed down by a barrier, such as mountain ranges or nunataks (exposed rocky part of a ridge or a mountain, not covered with ice or snow) within an ice field at its edge. When a meteorite falls over Antarctica, it is buried in snow, and sinks deeper over the seasons to end up enclosed in ice as the snow crystallizes under pressure. Ice flows as a sluggish hydraulic system. The meteorite follows the ice movement outward towards the edge of the continent, and ultimately into the ocean. When the ice flow is stopped or slowed down by an obstacle, the ice movement starts to be vertical. The wind subsequently strips the superficial snow and leads to a slow ablation of the ice. Over time, the meteorites collected from a large area and trapped deep in the ice layers are brought to the surface in local zones as the loss by ablation is replenished by upstream ice at depth. The patches of vertical ice flow are referred to as meteorite stranding surfaces. The low temperature reduces the weathering of the exposed meteorites. With patience and a good eye, numerous meteorites can be collected in the ice fields of Antarctica.

Samples from worldwide meteorite collections have been and are analyzed with the objective of relating their age and their composition to planetary evolution, of putting constraints on the chronology of differentiation processes and on the onset of plate tectonics and the recycling of the crust and implications for life sustainability.

Martian meteorites will also be addressed in this paper as putative evidence and highly controversial traces of Martian bacteria were reported in the martian meteorite ALH 84001, although there are alternative abiotic explanations.

The identification and preservation of life tracers is a very complicated subject that will be partly addressed in this paper. Life leaves traces by modifying microscopically or macroscopically the physical-chemical characteristics of its environment. The extent to which these modifications occur and to which they are preserved will determine the ability to detect them. By characterizing chemical and morphological biosignatures on macro- to micro-scale, preservation and evolution of life in early Earth or analogue habitats can be studied, with the objective to constrain the probability of detecting life beyond Earth and the technology needed to detect such traces. The Earth biosphere has been interacting with the atmosphere and crust at a planetary scale probably soon after its origin, in the Archaean, and most significantly since the 2.5 Ga oxygenation, with profound implications for planetary and biosphere evolution.

The paper is organized as follows. We first consider the definition of habitability and the conditions for life persistence (Habitability section). As habitability is related to the evolution of planetary systems, we review the accretion part of the history of planets on moons, the role and effects of impacts and of dynamical processes such as a magma ocean and plate tectonics (Accretion and evolution of planetary systems section). We in particular examine the case of Mars as it is the ideal test of early processes. In the same section, we further examine the influence on the solar illumination and solar wind on planets and atmospheres evolution, including as well the effect of impacts. This states the contexts of potential habitats and their evolution. Life, if it exists on a planet, must have enough time to be sustained and must then be preserved to be detected in samples. Life tracers and their preservation section treats of the biosignatures and their preservations. It includes description of extreme environments were extremophiles may survive.

2. Habitability

Defining the habitability of a planet requires not only to understand the range of physico-chemical conditions in which life – as we know it – can exist, but also to grasp the limits of life. Life actually originated and evolved from an "extreme" early Earth exposed to harsh ultraviolet (UV) radiation, sometimes heavy meteoritic bombardments, with no or very little oxygen in the atmosphere and oceans, conditions that were extreme compared to the present ones. The search for life in potential habitats requires the characterization of traces or indices of life (biosignatures) permitting its detection in ancient rocks (past life) or recent substrates, such as sediments, water, ice, or rocks (extant life). The presence of an atmosphere over a certain period of time (with sufficient pressure to have liquid water at the planetary surface) and its characteristics may be important to sustain life, as well as the interior of a planet, its evolution, its geodynamics, and its thermal state.

The terrestrial planets provide a substrate on which life may develop but the persistence of life depends also on the planetary evolution (van Thienen et al., 2007). Earth, Mars, and Venus are quite similar in composition, and Earth and Venus also in size, but the geodynamics of these planets are quite different: plate tectonics on Earth, possible episodic resurfacing on Venus, and a long-standing stagnant lid on Mars. The role of volatiles, specifically H_2O and CO_2, is not yet well understood although they must play an important role in the exchange between the solid planet and its atmosphere/hydrosphere, through subduction of hydrated crust and volcanism. The absence or presence of plate tectonics must be considered among the habitability conditions. These processes are mentioned in the literature (Franck et al., 2000a, 2000b; Guillermo et al., 2001; Parnell, 2004; van Thienen et al., 2007; Valencia et al., 2007; Lammer et al., 2009; Gillmann et al., 2009, 2011; Javaux and Dehant, 2010) but are not yet fully understood.

The loss of the atmosphere on Mars is considered as the main factor for the low probability of the existence of extant life on the surface of the planet, as no liquid water is present on the surface. The escape of the martian atmosphere is probably a combination of thermal and non-thermal processes such as charge exchange, dissociative recombination, sputtering, and ionization (Lammer et al., 2003), as well as asteroid or comet impacts (Pham et al., 2009). The atmosphere could be protected against these escape processes by the presence of a magnetic field as an extensive magnetosphere may help to retain escaping particles. The greenhouse effect is important as well in the definition of the habitable zone (HZ), by increasing the atmosphere mean temperature (Kasting et al., 1993). Franck et al. (2001) have related the boundaries of the habitable zone to the limits of photosynthetic processes, considering the evolution of the atmosphere through geological timescales. Dehant et al. (2007) and Lammer et al. (2009) have further studied the escape of the atmosphere and recognized the important influence of the existence of a strong magnetic field that protects life from severe radiation from the Sun and shields the atmosphere against erosion by the solar wind, as is the case for Earth. The CO_2 cycle and its exchange between the interior of the planet and the atmosphere (degassing/erosion/weathering) has been investigated (Spohn, 2007; Gillmann et al., 2006, 2009, 2011), taking into account the effects of volcanic degassing focusing on CO_2. High Extreme Ultraviolet (EUV) at the beginning of the Solar System history does also induce loss in some species of the atmosphere. Volatile exchange between the mantle and the atmosphere is a very effective mechanism influencing the atmosphere mass for planets with plate tectonics. In the case of a mono-plate system such as the planet Mars, most models of the evolution of the surface require removal of CO_2 from the atmosphere, in principle possible by carbonate precipitation. Carbon occurs on Mars as CO_2 gas in the atmosphere and as CO_2 ice in the Polar caps. The Tharsis volcanic province appeared in the early history of Mars and was accompanied by water and carbon dioxide emission in quantities possibly sufficient to induce a greenhouse effect and a warm climate (Phillips et al., 2001; Solomon et al., 2005). If there was ever a period of standing water on Mars, then theory requires that carbonate rocks form, since the atmosphere was rich in carbon dioxide (in the presence of water and silicate rocks, carbon dioxide from the atmosphere would have been drawn down into solid carbonates). However, since this large carbonate component never turned up, this assumption has been challenged recently and the presence of other greenhouse gases such as methane has been suggested to explain the absence of Noachian carbonates on Mars (Catling, 2007; Chevrier et al., 2007). Carbonates occur in the martian meteorite ALH84001 (Corrigan and Harvey, 2004; Halevy et al., 2011) and have been recently detected by CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) on MRO (Mars Reconnaissance Orbiter) (Murchie et al., 2007; Ehlmann et al., 2008), OMEGA (Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité) on Mars Express (Bibring et al., 2005) and by the Phoenix lander (Boynton et al., 2009). The occurrence of carbonates at the surface of Mars is however puzzling as carbonates dissolve quickly in acidic conditions and evidences from Terra Meridiani suggest that an acidic environment may have dominated the planet at the end of the Noachian, beginning of the Hesperian (Bibring et al., 2006; Ehlmann et al., 2008). The study of the different carbon reservoirs on Mars improves the understanding of Mars' carbon cycle (Wright et al., 1992; Grady et al., 2004). Recent modeling by Tian et al. (2009) suggests, contrary to the general hypothesis, a cold early Noachian period with an instable CO_2 atmosphere subjected to thermal escape. By mid to late Noachian (after 4.1 Ga), the solar EUV (Extreme Ultraviolet) flux would have decreased enough to permit volcanic CO_2 to accumulate and form a thick atmosphere and liquid water to be stable at the surface for a few hundred of Million—although recent thermo-chemical evolution models suggest that the degassing from the interior alone was not sufficient to obtain a thick atmosphere due to the lower oxygen fugacity of the Martian mantle in comparison to the Earth mantle (Grott et al., 2011). These calculations suggest that Mars and Earth were dissimilar in their early history, and underline the importance of the planet mass to retain its atmosphere and to maintain habitability (Edson et al., 2011). It also illustrates the fact that habitability may change through time.

The concept of habitability requires consideration of many more factors than simply the distance planet-star. These factors may include the planetary rotation with consequences on climate and magnetic field generation, the relationships between the planet mass/radius and the atmosphere and plate tectonics, the role of volatiles in the hydrosphere, atmosphere and plate tectonics, the atmosphere evolution, and the co-occurrence of an atmosphere and hydrosphere. The effects of all these geodynamic processes on the habitability of a planet and ultimately on the development and persistence of life must be recognized.

3. Accretion and evolution of planetary systems

The chronology of differentiation processes, the onset of plate tectonics and recycling of the crust and implications for life sustainability is investigated in this section. The role of impacts in the atmospheric evolution of the planets is examined as well. In addition meteorites deliver precious information about the early evolution of the Solar System and its solid bodies and in some case closely resemble the materials from planetary interiors. This will also be discussed in this section.

3.1. Role/effects of meteorites and comets impacts

Collision is a ubiquitous geological process in the Solar System that also directly affects planet Earth. Shortly after the collisional origin of the Earth–Moon system (Canup and Asphaug, 2001), a "late veneer" of small amounts of chondritic material from the asteroid belt (or beyond) is probably required to account for the volatile budget of Earth, including water (e.g., Albarède, 2009). It also accounts for the concentration of highly siderophile elements, such as the platinum group elements (PGE), in the terrestrial mantle and crust (e.g., Kimura et al., 1974). Later, around 4.0 Ga, the Late Heavy Bombardment (LHB, see, e.g., Morbidelli et al., 2005) could also have enhanced the budgets of some highly volatile elements, including noble gases (Marty and Meibom, 2007). Furthermore, during the Hadean (4.4–4.0 Ga), addition of cometary and carbonaceous asteroidal material, containing complex organic compounds, could be advocated to have played a major role in prebiotic processes and in the origin of life on Earth (e.g., Chyba and Sagan, 1992), in association with terrestrial processes (Benner et al., 2004; Benner, 2011; Forterre and Gribaldo, 2007). It could even be hypothesized that life may potentially have arisen, but was frustrated and/or wiped out by severe bolide impact (Maher and Stevenson, 1988) such as perhaps during the LHB.

In more recent times, the strong correlation between the Cretaceous–Paleogene (K/Pg) mass extinction and the formation of the 200 km Chicxulub impact crater, demonstrates the importance of impact events for the biological evolution of Earth (Schulte et al., 2009, 2010). However, the disruption of the L-chondrite parent body ~470 Ma ago (relatively (*L*)ow iron abundance chondrite) – the largest documented asteroid breakup during the past few billion years – coincides with abundant fossil meteorites and impact craters in the geological record and some suggest a possible causal link with the great Middle Ordovician (second of the six periods of the Paleozoic Era shown in Fig. 3) biodiversification event (Schmitz et al., 2008). If a cyclic periodicity can now be ruled out, the impact rate on Earth remains a matter of considerable debate and varies by a factor 5 to 10 according to different authors (Toon et al., 1997; Rampino and Stothers, 1984; Farley et al., 1998; Bottke et al., 2000; Tagle and Claeys, 2004; Chapman, 2004; Feulner, 2011). A key question is to identify the source and composition of the impacting projectiles: do they derive mainly from the asteroid belt and are they composed mostly of differentiated or undifferentiated bodies, or is a cometary origin also possible? One of the best-studied recent examples of elevated bombardment takes place during the late Eocene (~35 Ma ago, one epoch of the Paleogene Period in the Cenozoic Era) and is attributed to either an asteroid or comet shower (Farley et al., 1998; Tagle and Claeys, 2004). Crater peaks and/or concentrated ejecta layers do also occur during the Late Devonian (fourth of the six periods of the Paleozoic Era), Middle Ordovician, Early Proterozoic and Archaean (see Fig. 3, note that Archaean is also spelled Achaean). Recently Bottke et al. (2010, 2011) proposed that the latter two might constitute the tail end of the LHB (Late Heavy Bombardment).

3.2. Magma Ocean and plate Tectonics

Due to the heat released by short-lived isotope radioactivity, core formation, and impacts, the evolution of differentiated rocky bodies started with metal-silicate segregation and a magma ocean stage. These early geological processes determine the fate of each planet. The question here is why the planetary bodies, Earth and Mars in particular, started with similar geological processes but finally ended up differently?

One of the precise questions debated in the science community is the age of the shergottites martian meteorites. The classically accepted crystallization ages for these basalts are relatively young (~160 to 460 Ma see compilation in Nyquist et al., 2001), but recent geo-chronological studies using Pb–Pb dating have indicated older ages (up to 4.1 billion years (Ga, see Bouvier et al., 2005; Bouvier et al., 2009). The old age for shergottites would reconcile the observation of a largely old martian surface, obtained using crater counting (Nyquist et al., 2001). Paradoxically other geochemical studies have proposed consistent stories for the early differentiation of Mars that are incompatible with an old age of shergottites (see, e.g., Debaille et al., 2007). The gases trapped in the shergottites minerals constrain the composition of the martian atmosphere. Knowing if the measured composition is reflecting a 4 Ga or a 200 Ma old snapshot of the martian atmosphere is thus of major importance. While the presence of a magma ocean is well accepted for the early Earth, Moon, and Mars, it is clear that those planets have evolved differently after presenting a similar step in their evolution. Thermal and chemical processes have taken place during the earliest history of Mars, when the planet was most geologically active. Numerous hypotheses explain Mars striking hemispherical dichotomy in both topography and crustal thickness between the heavily cratered Southern highlands from the smooth Northern lowlands. Formation by an oblique giant impact is currently favored (Andrews-Hanna et al., 2008). However, endogenic models such as plate tectonics (Lenardic et al., 2004) and low-degree mantle convection (Zhong and Zuber, 2001) cannot be ruled out. Mantle overturn as a consequence of an unstable fractionated mantle after freezing of a magma ocean could also lead to substantial re-melting in the deepest mantle (Debaille et al., 2009). The existence of crustal remnant magnetization on Mars (Connerney et al., 1999) indicates that a dynamo operated for a substantial time early in martian history, but the timing, duration, and driving mechanism are unknown. Hypotheses include a super-heated core with respect to the mantle as a consequence of core formation (Stevenson, 2001; Breuer and Spohn, 2003) and plate tectonics (Nimmo and Stevenson, 2000).

Why is Earth the only planet of our Solar System showing plate tectonics? This question is of importance because the onset of plate tectonics could subsequently be related to its environment, habitability and the presence of life (Javaux and Dehant, 2010). Degassing related to subduction zones and intra-plate volcanoes replenishes an atmosphere in greenhouse gases, helping to maintain liquid water at the surface (Condie, 2005; see also Morschhauser et al., 2011, for the case of a one-plate planet as Mars). Also, erosion of tectonic uplifts provides elemental nutrients that are necessary to develop and sustain life (Anbar, 2004). Plate tectonics and associated hydrothermal activity play an important role in controlling in part the burial rate of organic material in sediments, oceanic nutrients, geographic biological isolation, with important implications on ocean and atmosphere chemistry and consequently on life's evolution. Hydrothermal activity was significantly higher in the Archaean, leading to silica-saturated ocean waters that promoted rapid preservation (by silicification) of biosignatures along with the production of abiotic organic molecules. However, it remains unclear why and when continuous subduction zones, defining a modern-style plate tectonics, appeared on Earth. Several lines of evidence suggest that plate tectonic was active very early in Earth's history (Martin et al., 2006; Shirey et al., 2008). However, recent studies also show that the onset of modern-style plate tectonics could have appeared relatively recently, around 3 Ga ago or even more recently (Shirey and Richardson, 2011; Stern, 2008).

3.3. Interior models based on geodesy and meteorites

This Section aims to a better understanding of the physical and dynamical properties of the interior reservoirs and their interaction with the atmosphere in terms of necessary heat and convection processes inside the geochemical internal reservoirs and in terms of magnetic field generation. The exchange between the different volatiles reservoirs and their implication on planetary evolution is also reviewed.

3.3.1. Interior structure of terrestrial planets and moons

Fig. 1 shows a possible model of the interior of Mars with its most prominent layers: crust, mantle, and core. The boundaries between these layers are characterized by density discontinuities indicative of changes in composition. Within these layers, density increases with depth in response to the increasing pressure but also as a result of phase changes, which have important implications for the convection and heat transfer. Models for the interior structure of Mars (Rivoldini et al., 2011) depend heavily on measurements of gravity, topography, and the response of the planet to periodic tidal forces (Konopliv et al., 2011).

Knowledge of the core state and size is crucial to understand a planet's history and activity (Mocquet et al., 2011). The evolution of a planet and the possibility of dynamo magnetic field generation in its core depend on the planet's ability to develop convection. In particular, a core magneto-dynamo is related either to a high thermal gradient in the liquid core (thermally driven dynamo), to the growth of a solid inner core (compositionally driven dynamo), or a combination of both (Breuer et al., 2010). The state of the core depends on the nature and percentage of light elements and temperature, which is related to the heat transport in the mantle. Indications from recent Mars satellite geodesy suggest that the core is at least partially liquid (Konopliv et al., 2006, 2011) and that the value of the radius of the martian core is uncertain to about 10% (Rivoldini et al., 2011).

3.3.2. *Mars: Ideal test of early processes*

Contrary to the plate tectonically active Earth, Mars may have retained evidence of its early differentiation and evolution. Martian meteorite compositions indicate melting source regions with different compositions that persisted since the earliest evolution of the planet (Borg et al., 2002; Debaille et al., 2007), suggesting that mantle convection, even though existing (Li and Kiefer, 2007), was not able to homogenize itself. Moreover, much of the martian crust dates to the first half billion years of the Solar System history (Hartmann and Neukum, 2001). Measurements of the interior are likely to detect structures that still reflect early planetary formation processes, making Mars an ideal subject for geophysical investigations aimed at understanding planetary accretion and early evolution.

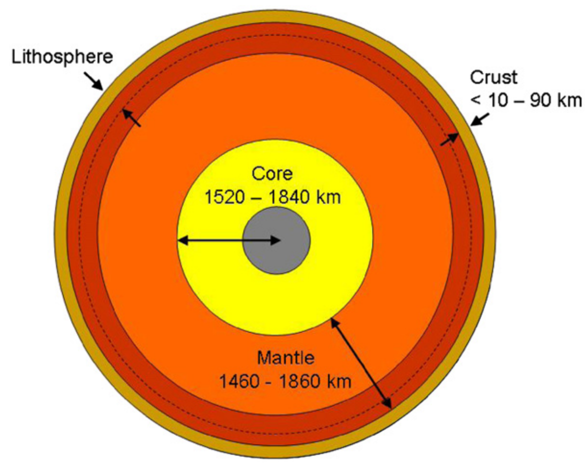

Fig. 1. Possible model for the interior of Mars. The other terrestrial planets have similar interior structures, with different relative dimensions of the reservoirs; the grey sphere inside the core indicates a (solid) inner core that is most likely not existent for Mars but may exist in the other terrestrial planets.

3.3.3. *Thermal evolution and convection*

Subsequent to initial differentiation, Mars, Venus, and Earth diverged in their evolution. Earth's thermal engine has transferred heat to the surface by lithospheric recycling but on Mars there is no evidence that this process ever occurred (e.g., Sleep and Tanaka, 1995). The thermal gradient determines the thickness of the elastic lithosphere and the depth of partial melting, which controls magma generation (e.g., Baratoux et al., 2011). Stagnant lid convection is the most basic regime for convection in fluids with temperature dependent viscosity and explains why most planets – apart from the Earth – have immobile lids covering their convecting deeper interiors.

Plate tectonics is important for habitability as it facilitates volatile exchange between the atmosphere and the interior. One-plate planets will also release volatiles but the recycling is a problem and such planets will increasingly frustrate volcanic activity by thickening their lids. Plate tectonics also cools the deep interior much more efficiently than stagnant lid convection. Continued efficient cooling of the deep interior is mandatory for keeping a magnetic field, which will protect the atmosphere and biosphere from the solar wind (Dehant et al., 2007). Fig. 2 illustrates the

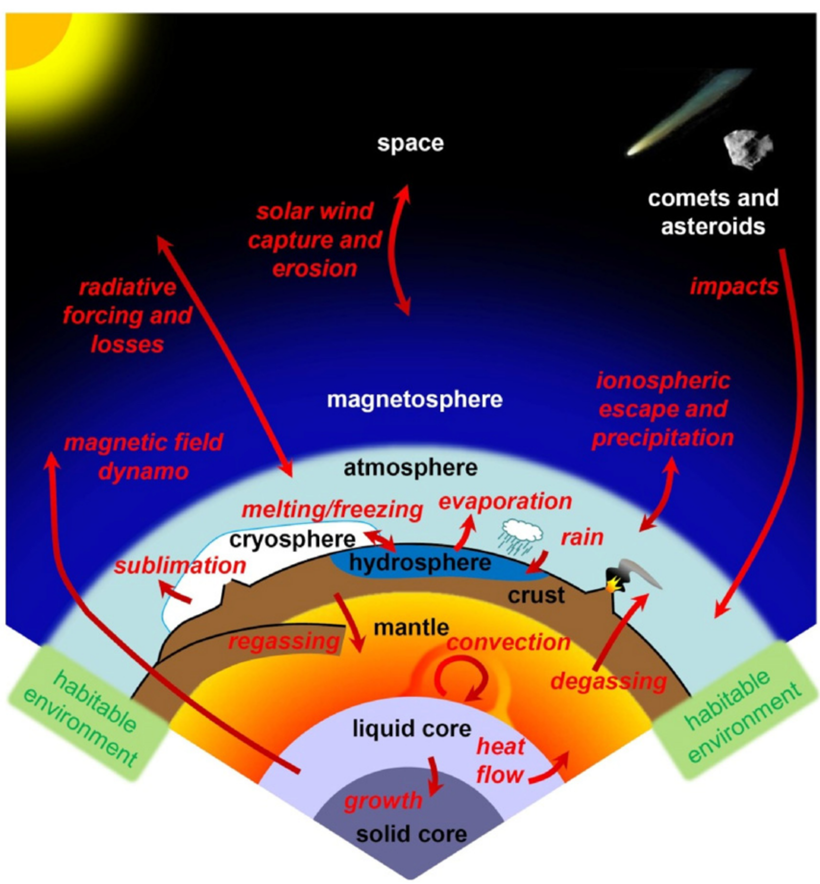

Fig. 2. Sketch with all the interactions between the reservoirs.

differences for interior-atmosphere interactions and life between plate tectonics and stagnant lid convection.

3.3.4. Global tectonics, magnetic field, and life

The global tectonic cycle that is associated with plate tectonics provides a continuous supply of ''nutrients'' through erosion, uplift, weathering, lateral transport, and fluvial movement. Early Mars had probably an intermittent wetter and warmer environment possibly protected by a magnetic field. However, the protecting magnetic field likely died before life had the time to significantly diversify (if it ever did) (Connerney et al., 1999). At about the same time as the disappearance of the magnetic field, the atmosphere eroded resulting in a limited greenhouse effect and a cold planet with a very limited atmosphere, preventing water to be liquid at the surface of Mars (Bibring et al., 2006).

3.3.5. Mantle cooling and magnetic field generation

For a magnetodynamo to exist, the core must be at least partially liquid and sufficient energy is needed to overcome the ohmic losses of the dynamo. Mantle cooling plays an important role in the magnetic field generation as it controls the temperature gradient at the core-mantle boundary. Thermally driven convection requires the heat flux out of the core to be larger than the heat flux that can be conducted along an adiabat. For a superheated core after core formation, the temperature gradient is large and an initial magnetic field is highly likely, even without plate tectonics. Due to fast cooling of an initially hot planet, the dynamo cannot be sustained for more than a few 100 Ma (million years) after planet formation. With plate tectonics that allows efficient core cooling, the phase of dynamo action can be prolonged by a factor of two even without a super-heated core (Breuer and Spohn, 2006).

After an initial phase of a magnetic field generated by thermal convection, compositional convection may start when a solid inner core starts growing, leading again to a core dynamo (Labrosse and Macouin, 2003). A pure iron core in Mars could currently be entirely solid, but with a small amount of a light element (in particular sulfur), the temperature of solidification decreases, keeping the core liquid longer in the history of Mars, maybe even to the present-time (Stewart et al., 2007). To maintain compositional convection resulting from iron precipitation onto the solid inner core, cooling of the planet is necessary.

3.3.6. Magnetic field evolution and other mechanisms for magnetic field generation

At present there is no active magnetic field on Mars. However, Mars possesses a remnant crustal magnetic field from a dynamo that was operational in Mars' early history (Acuña et al., 1999), sometime between core formation ($\sim$4.5 Ga) and the Late Heavy Bombardment. The driving force for the martian dynamo, the intensity and morphology of the generated field and the cause of the dynamo's stop are poorly understood.

On Earth, the present magnetic field is generated by compositional convection within the conducting core driven by the crystallization of the inner core. The earliest preserved traces of a paleomagnetic field suggest that the geomagnetic field has existed since at least 3.5 Ga (Tarduno et al., 2010), with a possible enhancement $\sim$1 Gyr ago when compositional convection started (Labrosse and Macouin, 2003).

Besides thermal and compositional convection driving a core dynamo, additional mechanisms may significantly modify the organization of fluid motions such as libration (Noir et al., 2009), precession (Meyer and Wisdom, 2011) and tides (Kerswell and Malkus, 1998) and may even be the cause of a dynamo at certain evolutionary stages of a planet. It is also likely that giant impacts generate (Lebars et al., 2011), as well as kill (Roberts et al., 2009) the dynamo. During the Late Heavy Bombardment, several martian impacts occurred within a relatively short period, towards the end of which the global magnetic field disappeared (Lillis et al., 2008). Finally, the occurrence of a major mantle overturn could also have decreased the thermal gradient between the core and the mantle, by injecting heat-producing cumulates rich in radioactive elements in the deep mantle (Debaille et al., 2009), hence inhibiting the magnetic field.

3.4. Solar illumination, solar wind, magnetosphere, impacts and atmosphere boundaries interactions for determining the net budget of atmospheric material

This Section deals with the thermal-chemical evolution of planetary atmospheres and its interaction with surface, hydrosphere, cryosphere, and space to determine the evolution of pressure, temperature, and composition in time, and the existence or not of liquid water.

The long-term evolution of the atmosphere of a planet depends on how material is lost from the atmosphere to space. Again, impacts of comets and meteorites are important. Planets are able to retain their atmospheres through gravitational binding and electromagnetic forces. Atmospheric particles that initially escape to space may return because of the interplay of these forces. The *net* loss of material must therefore be estimated by studying the escape mechanisms and the long-term evolution of the mass loss rates (Lammer et al., 2009).

3.4.1. Present states of the atmospheres

The primary atmospheres of terrestrial planets are almost completely lost, mainly through hydrodynamic escape and through removal by large impacts, and planets now possess secondary atmospheres, generated through degassing, internal volcanism or impact deliveries of volatile-rich projectiles (including comets). Fractionation in planetary atmospheres results mainly from the diffusive separation by mass of isotopic species, which occurs between the homopause (level where the diffusion becomes the controlling process) and the exobase (where collisions become rare). The lighter isotopes are preferentially lost and the heavier ones become enriched in the residual gas. Because Mars is smaller and has a lower gravitational field than Earth and because of the lack of any active magnetic dynamo, losses of volatiles to space (Jakosky et al., 1997; Jakosky and Jones, 1997) have been more extensive. It is important to determine whether the exchanges of volatiles on Mars could ever have provided the key chemical constituents that could sustain life. The increase in oxygen on Earth is a consequence of life developing oxygenic photosynthesis. Interestingly, the first step occurred at a time when the Earth underwent other major changes such as widespread Palaeoproterozoic glaciations (Bekker et al., 2004) and the formation and break-up of large continental blocks, increasing organic matter burial protected from oxidation and leading to oxygen accumulation in the ocean and atmosphere.

Planetary atmospheres derive from one or more reservoirs of primordial volatiles. The chemical and isotopic compositions of present-day atmospheres provide clues both to the characteristics of the source reservoirs and to the nature of the subsequent processing of the volatiles. The key diagnostic volatiles for tracing atmospheric origin and non-biogenic evolution are the noble gases, nitrogen as N_2, carbon dioxide as CO_2.

On the basis of isotopic data from the atmosphere and from components of the surface (martian meteorites) two major reservoirs of martian gases existed, an isotopically fractionated component that has undergone exchange and mixing with the atmosphere and a component that is unfractionated, and therefore represents the primary atmosphere composition. The ratios of D/H, $^{18}O/^{16}O$, $^{17}O/^{16}O$, $^{13}C/^{12}C$, $^{38}Ar/^{36}Ar$, and the isotopes of Xe reveal the most about the history of martian volatiles. These gases either reside primarily in the atmosphere (Ar and Xe) or play major roles in determining the climate (C, H, and O as CO_2 and H_2O).

3.4.2. *Escape processes*

The escape of particles from the upper atmosphere depends on atmospheric temperature, dynamics and composition. The thermal speed of atmospheric molecules may exceed the escape velocity and may lead to thermal Jeans escape. Especially the more volatile species are affected by this process (Chassefière and Leblanc, 2004). Any reaction that produces hydrogen, for instance, can lead to atmosphere losses (e.g., Barabash et al., 2007a). The temperature of the upper atmosphere, in particular, depends on the temperature in the lower atmosphere, on the incident solar electromagnetic radiation, and on the radiative transfer in the upper atmosphere. The study of the interaction of sunlight with the upper atmosphere of planets and planetary objects is thus of utmost importance. Note that this interaction changes through geological time.

Escape may be prevented by gravity. As the upper atmosphere is very tenuous and essentially non-collisional, a kinetic description of the gas particles is needed. Temperature and atmospheric tides are of prime importance. Planets are or may have been rapid rotators in their youth; centrifugal forces therefore should be taken into account. Planet–Moon distances also may have changed, implying for instance stronger tidal effects in the past.

Considering the progressive ionization of atmospheres with altitude, it is important to study the escape of charged particles. An electric field is set up so that the escaping stream of particles remains overall electrically neutral. Moreover, this outflow of charged particles is channeled by the planetary magnetic field, if present. Particles can escape into a planet's outer magnetosphere along "open" field lines, while they remain in the inner magnetosphere along "closed" field lines leading to the formation of a plasmasphere (Darrouzet et al., 2009). Time-dependent interactions between the magnetosphere and the solar wind, however, may ultimately eject such material from the magnetosphere into the interplanetary medium, or recycle it and bring it back to the atmosphere, e.g., by auroral precipitation (Morgan et al., 2011).

The situation is somewhat different for planets with an induced magnetosphere or for comets: there, the solar wind penetrates into the upper atmosphere, such that various other plasma processes may play an important role (e.g., Barabash et al., 2007b).

3.4.3. *Asteroid and comet impacts*

Impact erosion is a violent and effective process to alter a planet's atmosphere. Depending on the size of the planet, its atmosphere may be virtually blown off by a few large impactors. Even if the atmosphere is not removed it may be heated to a point where the planet becomes sterile and all biotic and pre-biotic molecules are destroyed. However, next to tectonic activity, impacts can be a major supply of volatiles and organic components, especially in the early history of a planet (Albarède, 2009; Chyba and Sagan, 1992). ESA (European Space Agency)'s Herschel infrared space observatory has recently found water in a comet with almost exactly the same composition as Earth's oceans. The discovery revives the idea that our planet's oceans came from comets (Hartogh, 2011). Large impacts affect the mantle convection and therewith also the core dynamo, which in turn affects the atmosphere. The frequency and strength of impacts are therefore important conditions for the development of an atmosphere on terrestrial planets.

The atmospheric escape caused by the impactors has been mostly studied by the help of complex hydrocode simulations (e.g., Pierazzo and Collins, 2003). Hydrocodes take into account material strength and a range of rheological models, to simulate in continuum medium the dynamic response of materials and structures to different types of impacts. The solutions of the numerical simulations for similar problems have not always been in agreement, mainly due to differences in the physical models such as the choice of an appropriate equation of state, or proper model of the vapor cloud dynamics. Pham et al. (2009) developed a rather simple model, which uses a parameterization of the major factors affecting atmospheric erosion and delivery. Such computationally inexpensive models capable of representing the basic aspects of impact erosion and delivery are particularly useful for the study of atmospheric evolution.

3.4.4. *Interaction with the cryosphere*

For Mars, it is believed that water is stored in the permanent North Polar cap, in the layered terrains of the North Polar cap and surrounding the South Pole, and as ice, hydrated salts, or adsorbed water in the regolith. The Polar caps are composed of Polar residual ice and Polar-layered terrain. The bulk of the residual cap is mainly water ice, but in winter each cap is covered with a seasonal coating of CO_2 ice. This seasonal cover extends to lower latitudes and can have a thickness of 1 m. The structure of the layered terrains presumably holds a record of the climate history of the planet. The layered terrain has a smooth surface that is almost free of craters, indicating that it is geologically young. The Polar caps are reservoirs for atmospheric H_2O and CO_2 (Malin et al., 2001). The formation of CO_2 clouds and snowfall during the martian Polar night is still far from understood. Presumably most of the CO_2 condenses directly onto the surface, but a fraction should also condense into snowflakes in the atmosphere, thus strongly influencing the radiative properties of the atmosphere and the martian surface (Forget et al., 1995). During the winter, both Polar caps are centered on the geographical poles. However, during the spring recession, they show different behaviors: the Northern cap retreats almost symmetrically, while the position of the Southern one becomes asymmetrical with respect to the pole. Besides their sizes, another difference between the two Polar regions is that in the North the seasonal CO_2 completely sublimes away during the local summer, while the South Polar region stays cold enough during summer to retain frozen carbon dioxide. In the North, water can therefore sublimate. It is transported southward and then precipitated or is adsorbed at the surface. The CO_2 condensation during winter in the Polar caps induces a 30% seasonal change in pressure. The atmospheric water concentration is controlled by saturation and condensation, and shows also a seasonal variation, through exchanges with the Polar caps, especially the Northern Polar cap (see e.g., Konopliv et al., 2011).

All the above processes have recently been described in a parameterized form (Pham et al., 2009, 2011; Lammer et al., 2012) that expresses the mass and energy fluxes between different atmospheric and/or magnetospheric reservoirs and interplanetary space. Such parameterizations allow predictions for prescribed planetary evolution scenarios, and the incorporation of this knowledge into a coupled model of the long-term evolution of a planetary system.

The model developed by Pham et al. (2009, 2011) for Mars, Venus, and Earth allows to compute the effects of impactors on the atmospheric evolution considering both the erosion of the atmosphere and the deliveries to it for different physical properties and impact flux scenarios. The hydrocodes developed based on the "tangent-plane" approach has been recently improved and adapted to impactor flux models that have been proposed (Gomes et al., 2005; Morbidelli et al., 2001, 2005). A summary of that work is presented in Lammer et al. (2012).

4. Life tracers and their preservation

This Section is related to the identification and preservation of life tracers, and the interactions between life and planetary evolution. It includes (1) looking at the preservation and evolution of life in early Earth or analogue habitats, (2) characterizing biogenicity criteria and methods applicable to the detection of morphological, chemical, isotopic, or spectral traces of life on early Earth and beyond Earth, and (3) evaluating the possible interactions between life and its hosting planet.

4.1. Identification and Preservation of life tracers in early Earth and analog extreme environments

4.1.1. Biosignatures

Defining life is a complex task (e.g., Gayon et al., 2010), but may not be necessary to look for its traces. Defining biosignatures, or traces of life indicative of past or present life, has been over the last few years the major strategy developed for the search of life on the early Earth and in the Solar System (Botta et al., 2008). Biomarkers, biosignatures or traces of life are used as synonyms (Javaux, 2011a). They include morphological (such as body fossils, biosedimentary structures such as stromatolites and other microbially induced sedimentary structures, and biominerals, Javaux, 2011b), isotopic (Thomazo and Strauss, 2011), and spectral biomarkers (Kalteneger, 2011). A general agreement is that extraterrestrial life will be carbon-based, cellular, and it will interact with its environment as habitat and source of nutrients. Consequently, it will leave chemical and/or morphological traces of these interactions, depending on the preservation conditions of the environment. Any strategy to look for life beyond Earth requires the characterization of biosignatures in locations that are not only possible habitats but also may preserve life traces. Geobiological studies in recent and past terrestrial environments can improve the understanding of preservational conditions and fossilization processes, and ultimately, permit to recognize traces of life on early Earth and possibly beyond. This is essential to choose landing sites, instrumentation, and samples to return for future exobiological missions.

Detailed petrology and geochemical analyses constrain the environmental conditions of preservation, differentiate biosedimentary structures from chemical/mineralogical precipitates or physical sedimentary processes, or provide key information on the composition of possibly biogenic, carbonaceous material. However, none of these techniques gives a definitive answer to the biogenicity of carbonaceous matter. It is the combination of multiple lines of evidence and the lack of abiotic explanations that diagnoses the biological origin. Deciphering the biogenicity of an object is difficult, even using cutting-edge *in situ* techniques (Javaux and Benzerara, 2009). Therefore, it will be challenging to find fossils in the Solar System beyond Earth (Javaux and Dehant, 2010), especially without being able to take samples back to Earth (Westall, 1999; Westall et al., 2000).

4.1.2. Early Earth traces

Possible traces of life found on early Earth sediments starting around 3.5 Ga, or more controversially around 3.8 Ga, include isotopic fractionations, biosedimentary structures (such as stromatolites and other microbial mats interaction with sediments), morphological fossils, and later, fossil molecules (e.g., review in McLoughlin, 2011). However, since abiotic processes may mimic life morphologies and chemistries, and contamination is possible, ambiguities and controversies persist regarding the earliest records (Brasier et al., 2006). For all types of biosignatures preserved in the rock records, the endogenicity (the signatures are inside the rock and not a contamination) and syngenicity (the signatures are as old as the hosting rock and were not incorporated later through borings or fluids in veins and pores) need to be evidenced by detailed *in situ* analyses even before addressing the problem of biogenicity (biological origin).

4.1.3. Endogenicity and syngenicity of life tracers

The endogenicity is evidenced by studying rock petrology and avoiding external contamination in sampling and laboratory procedures. The syngenicity is investigated by examination of geological context and petrology coupled with microscale analyses such as Raman microspectroscopy. The first step in the recognition of biosignatures is the determination of the environmental conditions of preservation. The samples should come from rocks of known provenance, of established age and demonstrating geographic extent. Moreover, the possible traces should occur in a geological context plausible for life: these criteria apply mostly for sedimentary environments (Buick, 2001; Javaux et al., 2010; Schopf et al., 2006; Sugitani et al., 2007) although some putative traces are reported in pillow lavas (e.g., McLoughlin, 2011).

4.1.4. Biogenicity of life tracers

For simple life forms, morphology of body fossils alone is not sufficient for determining their biogenicity, but needs to be combined with studies of populations (large fossil assemblage) with biological size ranges, the distribution showing fossilized behavior (orientation and distribution caused by mobility and interaction with the environment), cellular division, biogeochemistry, degradation patterns, hollow cellular morphology with traces of endogenous carbonaceous material, and the knowledge of the geological environment (Javaux and Benzerara, 2009; Javaux et al., 2010). The biogenicity of minerals (biominerals) is difficult to interpret, and abiotic auto-assembly of minerals or precipitation has been demonstrated in laboratory experiments simulating Earth surface conditions (Garcia-Ruiz et al., 2002) or meteoritic impact (review in Benzerara and Menguy, 2009). Noffke (2009) described the criteria for the biogenicity of microbially induced sedimentary structures in siliciclastic rocks, while Allwood et al. (2009) and McLoughlin et al. (2008) studied the biogenicity of stromatolites (microbially induced laminated carbonate rocks). Ichnofossils or traces of biological activities such as bioalteration of rocks are difficult to interpret (Lepot et al., 2009; Lepot, 2011; McLoughlin, 2011). The biological origin of complex molecules can be demonstrated by their complexity unknown in abiotic processes or non-random carbon number pattern (Derenne et al., 2008). Fisher-Tropsch-type (FTT) reactions (a set of chemical reactions that convert a mixture of carbon monoxide and hydrogen into hydrocarbons) occurring in hydrothermal conditions are known to produce C-rich and N-rich organic molecules with carbon isotopic fractionations similar to life signatures (McCollom and Seewald, 2006). The possibility that abiotic FTT carbonaceous material could mature through burial, diagenesis, and metamorphism into abiotic kerogen-like material, although plausible, still remains to be tested experimentally (De Gregorio et al., 2011). The biogenicity of isotopic markers is addressed in Thomazo and Strauss (2011). Spectral biomarkers are reviewed in Kaltenegger (2011).

4.1.5. Extremophiles

Extremophiles were among the earliest forms of life on Earth, still thrive today in a wide range of extreme environments, and possibly exist or could adapt beyond Earth (Javaux, 2006). Extremophiles include organisms from the three domains of life—Archaea, Bacteria, and Eukarya that thrive in extreme environmental conditions, which could resemble those existing beyond Earth. Extreme conditions can be physical (temperature, radiation, pressure) or geochemical (desiccation, salinity, pH, oxygen species, redox potential, metals, and gases). For example, extremophiles have been found in a wide range of environments on Earth, such as in the Dry Valleys of Antarctica, in the Atacama Desert of Chili, in the deep subsurface biosphere, hydrothermal vents and springs, in Polar ice and lakes, in vacuums and under anaerobic conditions (Rothschild and Mancinelli, 2001). Studying extremophiles is essential for defining the limits of life as known on Earth as well as for studying the preservation and detection of biosignatures in a range of physico-chemical conditions in early Earth and potential extraterrestrial habitats.

4.2. Implication of life tracers preservation for in situ detection on Earth and other planets

4.2.1. Radiation

Preservation of biosignatures depends on the original biological composition and on local environmental conditions. The Solar System is a harsh environment: it is pervaded by ionizing radiation such as cosmic rays, Solar Energetic Particles (SEP), Anomalous Cosmic Rays (ACR), and Radiation Belt Particles (RBP). Exposure of organisms to such ionizing radiation is life-threatening. However, a modest degree of modification of the genetic information by ionizing radiation ensures an enhanced mutation rate, and therefore may actually help the development of life (by increasing genetic variations on which natural selection operates). In general, ionizing radiation will have a detrimental effect on the preservation of life tracers. On Mars, the lack of a significant ozone layer and the low atmospheric pressure results in an environment with a higher surface flux of short wavelength UV radiation. Solar radiation reaching the surface is capable of interacting directly with biological structures. Calculations of the predicted levels of DNA damage of surface life on Mars show that it is approximately three orders of magnitude higher than that on Earth (Cockell et al., 2002). On the other hand, Sun's luminosity has increased with time, and was only two-third of present-time luminosity at the beginning of the solar system (Gough, 1981), thus with less negative effects.

4.2.2. Preservation of life tracers below the surface

Below the surface however, diagnostic organic molecules with isotopic signatures or cell walls may be preserved if protected by sedimentary layers or mineral incrustation. Mineralized morphological (cell casts) and biosedimentary signatures (''biofabrics'', including microbial mats), evidence of biomineralization and bioalteration, could be preserved as well, if proper habitats and fossilization conditions were present (Summons et al., 2011). Extant life could be protected in a hypothetic deep hydrosphere. Exobiology missions (such as Mars Science Laboratory (MSL) (Grotzinger, 2009), ExoMars (Vago et al., 2006)) and sample return missions will try to detect suitable samples for biosignatures using similar approaches and instruments as it is done for Earth samples, from a macroscale characterization of the geological context plausible both as habitat and preservation, to microscale analyses of possible biosignatures. An additional challenge will be to avoid Earth contamination, which may happen even if planetary protection protocols are in place.

4.2.3. Possible habitats on Mars

Habitats of extant life are less likely due to the scarcity of liquid water, unless deep aquifers occur, although some suggest that the presence of brines detected by Phoenix in the permafrost at the pole (Kereszturi et al., 2011) or possible occasional water spills (Komatsu et al., 2009) may be encouraging. If life ever appeared on Mars, it may have done so during the most habitable time period of the planet, the Noachian (before 3.8 Ga), and may be preserved in the oldest martian rocks. Favored targets by the space agencies are aqueous sediments or hydrothermal deposits (Summons et al., 2011), although life traces from hydrothermal deposits are often ambiguous because of the possibility of abiotic physico-chemical processes mimicking life.

4.2.4. Life tracers in meteorites?

As for early Earth traces of life, claims of finding traces of life in meteorites demands rigorous approaches, discarding contaminations, possibilities of abiotic origin, and requiring evidence for endogenicity, syngenicity and biogenicity of the putative biosignatures. For example, objects first described as nanobacteria at the surface of the Tatahouine meteorite, based on morphology, have been reinterpreted as abiotic calcite crystals (Benzerara et al., 2003). In 1996, putative traces of life have been reported in the martian meteorite ALH84001 by NASA (National Aeronautics and Space Administration of US) scientists (McKay et al., 1996). The martian origin of the meteorite, an orthopyroxenite that contains micrometric nodules of carbonate minerals, is not disputed. Its age has been debated because of the difficulty to date this rock due to its very low content in trace elements. The reported ages of ALH84001 ranges from 3.7–4.5 Ga, though not all of them have been interpreted as crystallization ages. The age obtained from K/Ar–^{39}Ar/^{40}Ar are 3.74 Ga (no error reported) (Murty et al., 1995), 3.92 ± 0.1 Ga (Ash et al., 1996), 4.0 ± 0.1 Ga (Ilg et al., 1997), 4.07 ± 0.04 Ga (Turner et al., 1997) and 4.18 ± 0.12 Ga (Bogard and Garrison, 1999). The ^{87}Rb–^{87}Sr age is 3.84 ± 0.05 Ga (Wadhwa and Lugmair, 1996) and the ^{147}Sm–^{143}Nd age is 4.5 ± 0.13 Ga (Harper et al., 1995). An age of 3.9 ± 0.04 Ga (^{87}Rb–^{87}Sr) and 4.04 ± 0.1 (Pb–Pb) Ga has also been interpreted as the time of secondary carbonate formation (Borg et al., 1999), while Wadhwa and Lugmair (1996) dated the formation of carbonates at 1.39 ± 0.1 Ga. The use of the ^{176}Lu–^{176}Hf system has set the final point of this debate, as this system gave the most precise age of 4.091 ± 0.030 Ga (Lapen et al., 2010). This age is corroborated by the ^{206}Pb–^{207}Pb ages at 4.078 ± 0.099 Ga obtained by Bouvier et al. (2009), that also reinterpreted the ages obtained by Borg et al. (1999) as the true crystallization age and not the age of the secondary carbonates. Concerning those carbonates, authors described mineralized rods and truncated octahedral magnetite crystals preserved in the nodules. These objects were compared to biological morphologies and interpreted at first as fossil nanobacteria (the rods) or biominerals (the magnetite crystals) (McKay et al., 1996). However these putative biosignatures can be explained by abiotic processes (see discussion in Knoll (2003); review in Benzerara and Menguy, 2009; but see Mckay et al. (2009) for an alternative view). Therefore, up to now, the hypothesis of an abiotic origin could not be falsified. The meteorite also included organic carbon in the form of large PAHs (polycyclic aromatic hydrocarbons), known to form biologically but also abiotically in interstellar medium. The study of this and other meteorites showed that rocky and organic material can be preserved for 4 Ga and transported from a planet to another within the solar system. Most importantly, it drove scientists to develop highly sensitive nanoscale analytical tools and to define rigorous biogenicity criteria, permitting to refine strategies for life detection on early Earth and beyond Earth.

4.2.5. Life and atmosphere

It is known that processes in planetary interiors can have immediate and large effects on the biosphere—e.g., volcanic eruption or seismic activity. The influence of life on the atmosphere and on the interior of planets is also of great importance.

The Earth biosphere has been interacting with the atmosphere at a planetary scale probably soon after its origin, in the Archaean, and most significantly since the 2.5 Ga oxygenation, with profound implications for planetary and biosphere evolution (e.g., Knoll, 2003; Roberson et al., 2011). Life affects the atmosphere of a planet through a series of mechanisms (Bertaux et al., 2007), in particular chemical reactions that produce and/or consume atmospheric gases.

The last decades have seen the increased capability of remote sensing. Spectra of (exo)planet atmospheres can be recorded from space- or ground-based instruments and atmospheric gases considered to be reliable ''biosignatures'' (CO_2, H_2O, O_2, O3, N_2O or CH_4) can be detected. However, Gaidos and Selsis, (2007) have shown that the presence of some of these signatures was not sufficient evidence for the presence of life (see Kaltenegger, 2011, for a recent review).

4.2.6. *Life and interior*

Effect of life on the interior includes the injection of biogenic material in subduction zones. The global tectonic cycle provides a continuous supply of ''nutrients'' through erosion balanced by uplift, denudation and lateral transport through fluvial movement. Tectonics also enhances organic matter burial, preserving it from oxidation, indirectly leading to increased ocean and atmosphere oxygenation, or may lead to increase of sedimentary and hydrothermal iron and silica concentration in the ocean. An example of this control on ocean chemistry is illustrated by fluctuations of ocean chemistry in the Precambrian, with alternating and/or periods of euxinic (sulfidic and anoxic) conditions (Canfield, 1998), anoxic conditions, or ferrous anoxic conditions (Planavsky et al., 2011), or contemporaneous spatially variable conditions in a stratified ocean (Johnston et al., 2009). These conditions may in turn limit trace elements availability and oxygen concentration, and may have consequences for life evolution (e.g., Anbar and Knoll, 2002; Lyons and Reinhard, 2009). The distribution of continental masses over the globe also affects the global ocean and atmosphere circulation, or may genetically isolate populations, with important implications on biological evolution.

5. Conclusion

The different sections of this paper question the existence of life on a planet by considering the interactions between the planetary interior, the atmosphere, the hydrosphere, cryosphere, space (including comets and meteorites impacts), and life in terms of habitability conditions. The evolution of the planetary system as a whole is controlled by its early conditions and dynamics. All these interactions must be integrated in order to refine the general understanding of the concept of habitability. As an example of interconnection, the possibility of having a net loss or gain of volatiles in the atmosphere depends on the atmospheric pressure itself (see Lammer et al., 2012).

By studying other planets, scientists seek to understand the processes that govern planetary evolution and discover the factors that have led to the unique evolution of Earth. Why is Earth the only planet with liquid oceans, plate tectonics, and abundant life? Mars is presently on the edge of the habitable zone, but may have been much more hospitable early in its history. Recent surveys of Mars suggest that the formation of rocks in the presence of abundant water was largely confined to the earliest geologic epoch, the Noachian age (prior to 3.8 Ga) (Poulet et al., 2005). This early period of martian history was extremely dynamic, witnessing planetary differentiation, formation of the core, an active dynamo, the formation of the bulk of the crust and the establishment of the major geologic divisions (Solomon et al., 2005). Formation of the crust and associated volcanism released volatiles from the interior into the atmosphere, causing conditions responsible for the formation of the familiar signs of liquid water on the surface of Mars, from abundant channels to sulfate-rich layered outcrops, phyllosilicate formations, and carbonate deposits (Poulet et al., 2005; Clark et al., 2005; Bridges et al., 2001; Ehlmann et al., 2008; Morris et al., 2010).

Our fundamental understanding of the interior of the Earth comes from geophysics, geodesy, geochemistry, and petrology. For geophysics, seismology, geodesy and surface heat flow have revealed the basic internal layering of the Earth, its thermal structure, its gross compositional stratification, as well as significant lateral variations in these quantities. For example, seismological observations effectively constrained both the shallow and deep structure of the Earth at the beginning of the 20th century, when seismic data enabled the discovery of the crust-mantle interface (Mohorovičić, 1910) and measurement of the outer core radius (Oldham, 1906), with a 10 km accuracy (Gutenberg, 1913). Soon afterwards, tidal measurements revealed the liquid state of the outer core (Jeffreys, 1926), and the inner core was seismically detected in 1936 (Lehmann, 1936). Subsequently, seismology has mapped the structure of the core-mantle boundary, compositional and phase changes in the mantle, three-dimensional velocity anomalies in the mantle related to sub-solidus convection, and lateral variations in lithospheric structure. Additionally, seismic information placed strong constraints on Earth's interior temperature distribution and the mechanisms of geodynamo operation. The comprehension of how life developed and evolved on Earth requires knowledge of Earth's thermal and volatile evolution and how mantle and crustal heat transfer, coupled with volatile release, affected habitability at and near the planet's surface. The main steps in the history of the Earth are presented in Fig. 3.

Recent efforts in space exploration with spacecraft, landers and rovers – Mars Express (Chicarro, 2002), Mars Exploration Rovers (Squyres et al., 2003, 2004a, 2004b), Venus Express (Svedhem et al., 2007)… have provided new opportunities to investigate the possibility of life beyond Earth and especially the habitability of the two closest terrestrial planets, Mars and Venus. Neither Venus nor Mars presently have liquid water reservoirs on their surfaces – Venus has very high surface temperatures due to an excessive greenhouse effect (Bullock and Grinspoon, 2001) while Mars surface is very cold with a nonexistent greenhouse effect (Forget and Pollack, 1996; Haberle et al., 2004; Forget et al., 2007). Nevertheless, they could have had, early in their history, the atmospheric conditions necessary to sustain the presence of liquid water on their surfaces. Water is among the habitability

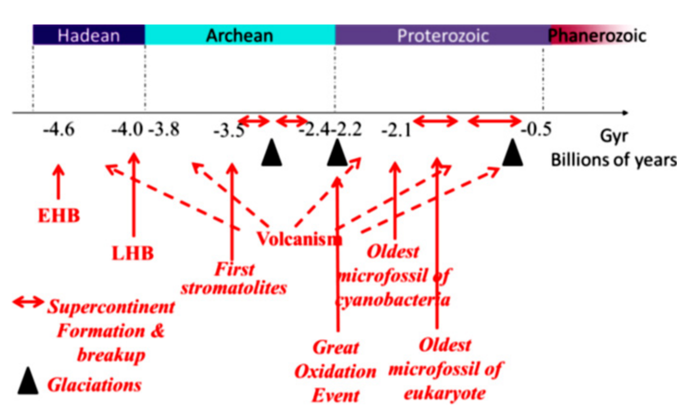

Fig. 3. Earth's history.

conditions that have been developed and considered from different scientific perspectives on different spatial and time scales (see Lammer et al., 2009; Javaux and Dehant, 2010, for reviews). The surface temperature and the presence of an atmosphere form the essential ingredients for water/life to appear. The planet Mars could have been habitable at the beginning of its evolution, as the examination of its surface suggests the existence of water very early on (about 4 Ga ago, see Fig. 4) (Bibring et al., 2005, 2006). Since then, Mars lost most of its atmosphere, preventing the presence of liquid water at the surface. In comparison Earth is habitable at present and has been so for at least 3.5 Ga.

Venus may have been habitable in its infancy with water and Earth-like oceans (Lammer et al., 2009). Venus has probably lost its water due to a runaway greenhouse effect. The "runaway greenhouse" occurs when water vapor increases the greenhouse effect, which, in turn, increases the surface temperature, leading to more water vapor that heats the atmosphere (Ingersoll, 1969). Another scenario leading to the same loss is the "moist greenhouse", where water is lost once the stratosphere becomes wet but in which most of the water of the planet remains liquid (Kasting, 1988). A better insight into atmospheric evolution in general can be obtained by comparative analysis of Earth with its neighboring terrestrial planets Venus and Mars.

As explained previously, all three terrestrial planets experienced a significant flux of meteorites and comets during the early history of the Solar System, which likely had consequences on the atmospheric evolution, on the habitability, and possibly even on the origin of life. Models capable of representing the basic aspects of impact erosion and volatile delivery have been developed for the study of atmospheric evolution. These models must be coupled to models of escape processes. All these processes, including impact erosion, depend on the atmospheric state (in particular the pressure). The stand-off distance of the magnetopause as determined from different magnetic field evolution scenarios (from internal thermal states) determines the size of the magnetosphere and the viability of escape mechanisms. Further influence from the initial state of the thermal conditions and possibly of an atmosphere will be considered as initial conditions of the overall model.

In this paper, we have identified some major characteristics of a planetary system, in so far as they relate to mass reservoirs and their couplings. We can define a number of "habitability indicators". In principle, we are able to trace – for a broad range of hypothetical planets near a variety of hypothetical Suns – how such planets evolve through time. By considering the habitability indicators for each planet simulation, we can find out whether

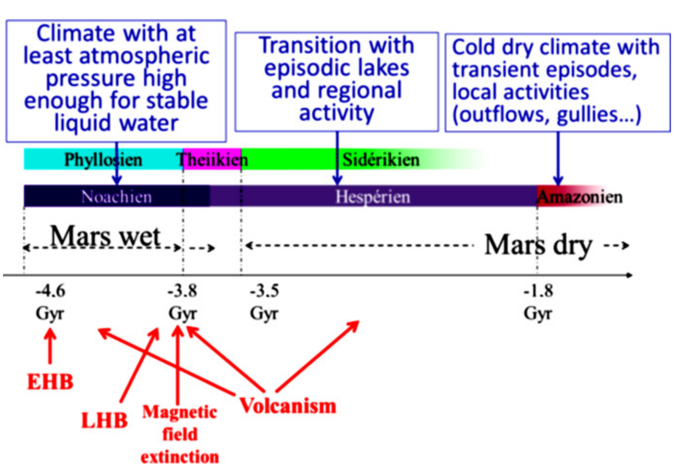

Fig. 4. Mars' history, considering the major periods as described by Bibring et al., 2005, 2006. ELH and LHB mean early and late Heavy Bombardment.

planets start off with being habitable and then cease to be so, or whether planets remain habitable for only a limited fraction of their lifetime, or whether planets in general appear to be non-habitable, which help us to identify which habitability indicators are the more relevant ones.

For example, it may appear from a global systems understanding that the study of habitability on Enceladus should focus first on tidal effects (to understand the energy source), on properly detecting a magnetic field signature (to unambiguously identify a subsurface liquid ocean), on *in situ* analysis of geyser material (to determine the composition of this ocean), on radar studies (to determine the thickness of the overlying ice), setting the stage for a later on *in situ* sampling by drilling through the ice into the ocean.

It is interesting to note that the elements forming the basis of terrestrial life (H, C, and O) are also key elements controlling large-scale planetary processes. The new field of Astrobiology investigates the biological and physical aspects of the topic, and places life in a planetary context. In this paper, we have addressed the planetary science aspects in studying the ability of planets to host life, their habitability in including life as a biogeochemical process into evolution modeling.

Finding life beyond Earth is one of the greatest challenges in science. The task is extraordinarily demanding and has been embraced by space agencies in the International Space Exploration Initiative. Based on the study of mechanisms presented in this paper, we have obtained a better view of the physical/chemical processes and thus of the relevant parameters. With this multi-disciplinary view in mind, we may pretend to point out fruitful ways to study the habitability of planets and moons and therewith lead to detailed roadmaps for assessment of their habitability.

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