SGI 09/06 118 Bollettino

Boll. Soc. Geol. It., 125 (2006), 000-000, 6 ff.

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Water and the evolutionary geological history of Mars

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ABSTRACT

Mars and Earth are the only two planets known to have long histories of dynamical cycling of water through their atmosphere, lithosphere, and cryosphere. Although we have known for thirty years that Mars had an early history with aqueous activity on its surface, exciting new results from current Mars missions are only now revealing the extensive sedimentary evidence of that history. Early Mars had extensive lakes and probably transient seas that were associated with a climate capable of generating the precipitation and runoff to sculpt its landscape and fill sedimentary basins. Well-preserved fluvial deltas show that early Mars was surprisingly Earthlike in its geological processes. The immense quantity of water implied for sequestering in the Martian permafrost (as ground ice) and beneath it (as ground water) requires an explanation as to the history of water recycling. These and other anomalous aspects of Martian geology are explained by a theory that incorporates the onset and termination of a core dynamo, associated with an early regime of plate tectonics during the first few hundred million years of the planet's history. Rapid accretion of thickened continental crust, as modified by concurrent high impacting rates, volcanism, and denudation, ultimately resulted in the southern highlands. Following cessation of the dynamo, the plate-tectonic regime terminated with zones of focused subduction in the Tharsis and Elysium areas. The resulting high concentration of water and other volatiles in the Martian deep mantle led to the Tharsis and Elysium superplumes, the long-term persistence of which is responsible for much of the volcanism, tectonism, water outbursts, and climate change that mark the subsequent, 4 billion year geological history of Mars.

KEY WORDS: *Mars, Planetary evolution, Comparative Planetology, Plate tectonics, Dynamo, Tharsis, Climate; Floods.*

RIASSUNTO

L'acqua e l'evoluzione geologica di Marte.

Marte e Terra sono i soli due pianeti conosciuti ad avere lunghe storie di cicli idrologici attraverso la loro atmosfera, litosfera e criosfera. Anche se già da trent'anni conosciamo che Marte ha avuto una storia iniziale con attività idrologica sulla sua superficie, solo ora i nuovi stimolanti risultati delle attuali missioni marziane stanno rivelando l'ampia evidenza sedimentaria di questa storia.

Inizialmente Marte aveva estesi laghi e probabili mari transienti che erano associati ad un clima capace di generare precipitazioni e fenomeni erosivi in grado di modellare il paesaggio e di riempire i bacini sedimentari. La presenza di ben preservati delta fluviali indica che il pianeta Marte nelle sue fasi iniziali era sorprendentemente simile alla Terra nei suoi processi geologici.

L'immensa quantità di acqua incamerata nel permafrost marziano (come ghiaccio sotterraneo) e al di sotto di esso (come acqua sotterranea) richiede una spiegazione allo stesso modo della storia del riciclaggio dell'acqua. Questi e altri aspetti anomali della geologia marziana sono spiegati da una teoria che incorpora l'innesco e la fine di un nucleo caratterizzato da una dinamo, associata con un regime iniziale di tettonica a placche durante le prime centinaia di milioni di anni di storia del pianeta. La rapida accrezione di una crosta continentale ispessita, × modificata da concomitanti fattori ad alto impatto, come vulcanesimo e denudamento, ha concorso alla formazione degli «highlands» meridionali. A seguito dell'interruzione della dinamo, il regime della tettonica a placche terminò con zone di localizzata subduzione nelle aree del Tharsis ed Elysium. La risultante alta concentrazione di acqua e altri volatili nel mantello profondo marziano sviluppò i «superplumes» di Tharsis e di Elysium, la lunga persistenza dei quali è responsabile per gran parte del vulcanesimo, del tettonismo, delle repentine fuoriuscite di acqua e dei cambiamenti climatici che hanno caratterizzato i successivi 4 miliardi della storia geologica di Marte.

TERMINI CHIAVE: *Marte, Evoluzione planetaria, Planetologia comparata, Tettonica a placche, Dinamo, Tharsis, Clima, Inondazioni.*

1. INTRODUCTION

Are planets individuals, formed by stochastic processes, such that their unique histories resist the spirit of generalization that propels the astrophysical sciences? Is it possible to present a self-consistent, physically coherent conceptual model that integrates all new discoveries, particularly those most anomalous in regard to the currently prevailing paradigms? If a general theory of terrestrial planet evolution is indeed possible, recent discoveries from spacecraft missions suggest that the role of water will be absolutely essential to that theory. Moreover, Earth is not the only planet with a long history of water-related hydrological cycling that is accessible to detailed investigation. Data from recent spacecraft missions show that Mars, like Earth, has a long history of dynamical cycling of water through its atmosphere, lithosphere, and cryosphere.

The concept of the hydrological cycle is one of the great achievements for the human understanding of nature. Arguably the premier hydrologist for all intellectual history was Leonardo da Vinci. Leonardo held two simultaneous views of Earth's hydrological cycle, as follows: (1) water cycles in the manner described in modern textbooks, with evaporation from the ocean leading to atmospheric transfer and precipitation over the land, followed by runoff back to the ocean; and (2) a water cycle via internal processes in which subsurface pressures from within the Earth force water upward (much as blood is pumped in the human body) to emerge from springs that produce runoff back to the ocean, from which the subsurface reservoirs are recharged. After 500 years, Earth has mainly been shown to follow (1), but the paradox of Leonardo's cycles remains very real for the planet Mars, where huge outburst floods of water emerged from subsurface sources (BAKER & MILTON, 1974; BAKER, 1982).

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This paper will provide a self-consistent, physically coherent conceptual model to integrate new spacecraft mission results concerning the geological evolution of Mars in relation to its water. In doing so, it will combine two earlier concepts. The first of these involves an understanding of later Martian history in terms of episodic, short-term hydro-climatic changes (BAKER *et alii*, 1991): MEGAOUTFLO - **M**ars **E**pisodic **G**lacial **A**tmospheric **O**ceanic **U**pwelling by **T**hermotectonic **O**utbursts (BAKER *et alii*, 2000). The second involves global geophysical and geological syntheses of early Martian evolution (BAKER *et alii*, in press): GEOMARS – **G**eological **E**volution **O**f **M**ars **A**nd **R**elated **S**yntheses (BAKER *et alii*, 2002). Regardless of the eventual truth to these conceptual schemes, their elaboration in this paper will highlight critical issues of Martian geological evolution in relation the history of its water.

2. AGE DATING

Other than radiometric dates on the small number of Mars-derived meteorites found on Earth, ages for the Martian crust must derive from the size-frequency relationships of impact craters that are superimposed on the Martian surface. Relative differences in crater densities are correlated to age (1) according to cratering rates that are determined from studies of Mars-crossing asteroids and (2) from comparisons to the radiometrically dated lunar crating rate (HARTMANN & NEUKUM, 2001). These studies define an «early Mars» epoch, the Noachian, as prior to 3.7 Ga. The later Mars epochs are then divided into the Hesperian, from about 3.7 to 3.0 Ga, and thereafter the Amazonian.

The crater ages for early Mars are a matter of current controversy. One school of thought (Age Model A) presumes a progressive decline of cratering from the very high rates that immediately followed accretion. Applying this assumption, H. Frey (FREY, 2006) identified numerous quasi-circular depressions (QCDs) on Mars, which he interpreted as ancient buried impact basins that formed progressively during the Noachian. Frey's interpretation divides the Noachian into phases centered on formation of the giant 2000-km diameter Hellas basin, which he dates as 4.08 Ga. The QCDs and crustal formation occurred prior to this event (FREY, 2006).

An alternative interpretation of early Mars cratering, Age Model B, presumes that there was a precipitous decline in the cratering rate shortly after accretion, around 4.5 Ga. This period of reduced cratering lasted until about 4.0 Ga, at which time there was a short, intense «late heavy bombardment» during which the very large impact basins all formed at around 3.9 Ga. The heavy bombardment was then followed by a greatly reduced cratering rate extending up to the present day. This scenario applies to the entire inner solar system (STROM *et alii*, 2005). There is currently a raging controversy between proponents of Age Models A and B.

3. THEORIES

3.1. MIDDEN AND MEGOUTFLO

Based on a selective interpretation of the Mars fluvial history, a common view, persisting up to the late 1990s, is that nearly all the aqueous activity on Mars was concentrated into the Noachian epoch. For convenience I label this the MIDDEN hypothesis (**M**ars **I**s continuously **D**ead and **D**ry, **E**xcept during the **N**oachian). The MIDDEN hypothesis developed, in part, because a great many fluvial valley networks occur in the old cratered highlands of Mars, leading to the view that nearly all of them formed during the period of heavy cratering rates of the Noachian (CARR, 1996), as presumed by the MIDDEN hypothesis.

Anomalously for MIDDEN hypothesis, Mars' outflow channels operated mostly during post-Noachian periods of Martian history. In contrast to the valley networks, these channels involve the immense upwelling of cataclysmic flood flows from subsurface sources (BAKER & MILTON, 1974). The transition from a more aqueous phase in the Noachian, with a progressively thickening ice-rich permafrost zone in post-Noachian time, is the basis for theories that explain the outflow channels as products of subsurface water that was confined by this process (CARR, 1979; CLIFFORD & PARKER, 2001). Certainly, there is strong evidence that much of the Martian surface is underlain by a thick ice-rich permafrost zone, a «cryolithosphere» (KUZMIN *et alii*, 1988). Nevertheless, the geological record shows that valley formation extended to long after the Noachian, and Amazonian-age valley networks are extensively developed on some Martian volcanoes (GULICK & BAKER, 1989, 1990). Mars displays many other areas of post-Noachian volcano-ice-water interactions, many of which are associated with channels and valleys. Strong indications of inadequacies in the MIDDEN hypothesis appeared in the late 1990s, when new spacecraft imaging data provided the extensive evidence for very recent water-related landforms (BAKER, 2001).

An alternative to the linear model of cryosphere thickening is that outflow channel activity is related to episodic heat flow and volcanism (BAKER *et alii*, 1991). Labeled «the episodic ocean hypothesis» by Carr (CARR, 1996), the BAKER *et alii* theory was initially considered to be outrageous (KERR, 1993). However, its general consistency with the new spacecraft data has resulted in the regeneration of this hypothesis as MEGAOUTFLO – «**M**ars **E**pisodic **G**lacial **A**tmospheric **O**ceanic **U**pwelling by **T**hermotectonic **O**utburst» (BAKER *et alii*, 2000).

MEGAOUTFLO envisions long periods (perhaps on the order of 10^8 years) in which Mars has a stable atmosphere that is cold and dry like that of today, with nearly all its water trapped as ground ice and underlying ground water. This long-lasting stable state is punctuated by relatively short-duration (perhaps 10^4 to 10^5 years) episodes of quasi-stable conditions that are warmer and wetter than those at present. At least one of these episodes may have occurred in relatively recent geological time (last 10^6 to 10^7 years). The episodes are separated by long periods (10^7 to 10^8 years) of stable, cold-dry conditions. All the major warm/wet episodes seem to have been associated with outflow channel activity and with extensive volcanism (BAKER *et alii*, 1991). The outbursts of water on to the planetary surface generated extensive ponding on the northern plains (FAIREN *et alii*, 2003), the geomorphological evidence for which was recognized earlier (JONS, 1985; LUCCHITTA *et alii*, 1986; PARKER *et alii*, 1989; GULICK & BAKER, 1990). During the outbursts of late Hesperian time, about 3.4 Ga, these sediment-charged

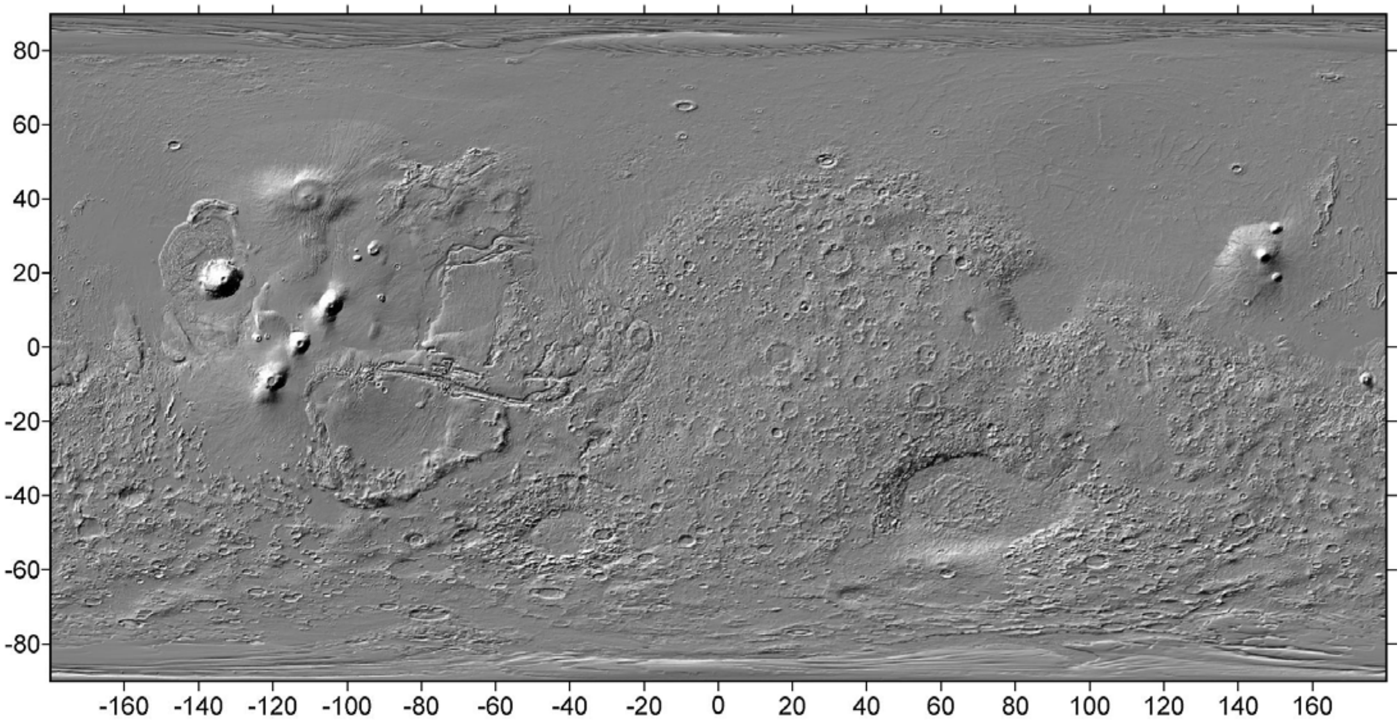

Fig. 1 - Shaded relief map of Mars, showing major features mentioned in the text, including Tharsis (centered at about 0 degrees Lat., –110 degrees Long.), Elysium (at 20 degrees Lat., 140 degrees Long.), and Hellas (at –40 degrees Lat., 70 degrees Long.).
– Carta orografica ombreggiata di Marte mostrante I principali elementi descritti nel testo, inclusi Tharsis (posizionato a circa 0 gradi di Lat., –110 gradi di Long.), Elysium (a 20 gradi di Lat, 140 gradi di Long.) ed Hellas (a –40 gradi di Lat., 70 gradi di Long.).

floods created hyperpycnal conditions upon entering the temporary mega-lake (Oceanus Borealis) that occupied the northern plains. The sediments emplaced subaqueously in this water body constitute the Vastitas Borealis Formation, which covers over 3×10^7 km^2 of the northern plains.

3.2. Geomars

GEOMARS – Geological Evolution Of Mars And Related Syntheses (Baker *et alii*, 2002) envisions a very ancient phase of plate tectonics could have generated the Martian highland crust by continental accretion (Baker *et alii*, in press). Concentrating volatiles in a local region of the Martian mantle, the subducting lithosphere during this early plate-tectonic phase would have led to a long lasting superplume at Tharsis. The resulting immense concentration of volcanism at Tharsis would itself greatly influence climate change (Phillips *et alii*, 2001) and the generation of megafloods, in analogous fashion to Earth plume centers (Komatsu *et alii*, 2004). The persistence of this volcanism episodically through later Martian history, would provide a mechanism for the episodic, short-duration aqueous phases that generated transient «oceans» and fluvial landforms.

Internal planetary heat provided the trigger for the massive outflows that transformed Martian climate during the geologically short epochs of ocean formation. Superimposed on the long-term monotonic decline in mantle heat flux for Mars were short-duration episodes of higher heat flow to the surface. Such episodes of higher heat flow seem consistent with the magmatic and tectonic history of Mars (Dohm *et alii*, in press).

4. ANOMALIES IN NEED OF EXPLANATION

Recent spacecraft mission discoveries have highlighted a great many anomalies in regard to currently prevailing paradigms for the geological history of Mars.

4.1. Crustal dichotomy

Mars is the only other terrestrial planet that, like Earth, has a distinctly bimodal hypsometry. For Mars this results from discrete highlands to the south and vast low-lying plains in the north of the planet (fig. 1). The Martian crust also shows major variations from thin beneath the northern plains (~30 km) to thick (~60 km) beneath the southern highlands and Tharsis (Zuber *et alii*, 2000; Neumann *et alii*, 2004). The origin of the great hemispheric dichotomy between the low-lying northern plains and the elevated southern highlands is the subject of unresolved multiple hypotheses, including mantle convection associated with core formation (WISE *et alii*, 1979), a colossal impact that formed a basin in the north polar region (Wilhelms & Squyres, 1984), extensive southward erosional retreat of the heavily cratered highland plateau (Scott, 1978; Hiller, 1979), and plate tectonics (Sleep, 1994).

The discovery of QCDs on the northern lowlands (Frey *et alii*, 2002), as noted above, led to the conclusion that the lowlands/highlands dichotomy on Mars formed very early. Based on Age Model A, Solomon *et alii* (2005) date that dichotomy and crustal differentiation to about 4.5 Ga. This assumption leads them to reject some possible explanations for the dichotomy, including (1) solid-state mantle flow (Zhong & Zuber, 2001), and (2) an early episode of plate tectonics similar to what SLEEP (1994) proposed for later Martian history. The reasoning is simply that these processes require too much time to fit within the narrow window allowed by Age Model A. SOLOMON *et alii* (2005) favor formation of the Martian crustal dichotomy by spatially heterogeneous fractionation of an early magma ocean.

4.2. MAGNETIC ANOMALIES

The spectacular discovery of anomalies of very strong remnant magnetism in portions of the Martian crust (ACUNA *et alii*, 1999) has huge implications for the early history of Mars. The anomalies probably formed when crustal iron-bearing minerals acquired magnetic remnance in the presence of a very strong magnetic field generated by an aggressively active core dynamo (CONNERNY *et alii*, 1999). Hellas, Argyre, and other young impact basins lack associated strong anomalies, probably because of demagnetization by the impact processed that formed them. The dynamo must have ceased at the time of basin formation, during the Noachian Epoch, about 4 billion years ago (ACUNA *et alii*, 1999), since the older areas of the highlands crust preserve the magnetic signatures.

The lack of magnetic anomalies on the northern plains of Mars is very puzzling if one adheres to Age Model A. The QCDs on the northern plains (FREY *et alii*, 2002), according to Age Model A (FREY, 2006), suggest that both the highlands and the plains developed very close to each other in time and very early in Martian history. Could the core dynamo have arisen, generated the remnant magnetism of parts of the southern highlands crust, then abruptly ceased just before the northern plains formed at close to 4.5 Ga, long before the giant impact basins at 4.1 Ga? SOLOMON *et alii* (2005) attempt to resolve this paradox by invoking hydrothermal demagnetization on an immense scale, a process for the whole northern plains that would require enormous volumes of water circulated to depths of tens of kilometers (HARRISON & GRIMM, 2002). A simpler possibility is that Age Model B is correct, in which case there is a period of about 500 million years available for all the relevant processes to occur.

4.3. ANDESITE

Andesitic compositions characterize the surface materials («Surface Type 2») overlying the relatively thin crust of the low-lying northern plains, while basaltic surface materials («Surface Type 1») overlie the much thicker highland crust (BANDFIELD *et alii*, 2000). These data can be consistently explained by having both igneous rock types forming in a hydrous fractional crystallization series typical of terrestrial subduction zone settings (MCSWEEN *et alii*, 2003). In contrast, the basalt compositions of the SNC (Mars-derived) meteorites are consistent with dry fractional crystallization, and probably represent relatively young surficial lavas derived from upper mantle sources that are depleted in volatiles.

An earlier view that the more silicic compositions of the northern plains might be simply the result of surficial alteration does not accord with elemental data from the Mars Odyssey Gamma Ray Spectometer (KARUNATILLAKE *et alii*, in press).

4.4. GRANITE

Recent identification in highland areas of local, deep crustal rocks of likely granitic composition (BANDFIELD *et alii*, 2004) provides another tantalizing clue, suggesting that the silica-rich surface materials on the northern plains could be derived from deep highland sources. Various channels and valleys would have delivered these highland-derived sediments to the northern plains. More recent work shows that the granites extensively underlie the Sytis Major region (BANFIELD, 2006), which is on the northern edge of the highlands. If granite compositions underlie portions of the highlands surface (mantled mainly by basalts), this might also explain why the southern highlands have relatively low surface densities, about 2.5 g/cc according to NIMMO (2000). These low densities contrast with the 3.1 g/cc surface densities of the basaltic Tharsis volcanoes (MCKENZIE *et alii*, 2002).

4.5. LAYERED UPPER CRUST OF HIGHLANDS

The usual model applied to the long-term movement of subpermafrost groundwater on Mars (CARR, 1996; CLIFFORD, 1993) presumes that the crust consists of blocky, porous «megaregolith» formed during the heavy bombardment by the intense fracturing of basement and overlain by interbedded crater ejecta and lava flows. However, recently acquired data show that the upper crust of Mars is extensively layered to depths of several kilometers, probably with both sedimentary and volcanic rocks that reflect a long period of large-scale erosion and deposition within what is now the ancient heavily cratered terrain (MALIN & EDGETT, 2001). This early phase of sedimentation probably coincides with an early history of Earth-like precipitation (both rainfall and snowfall) and surface runoff, leading to extensive fluvial denudation (CRADDOCK & HOWARD, 2002). A particularly striking complex of ancient meandering alluvial channels, comprising a fan-delta partly filling the crater Eberswald or NE Holden (MALIN & EDGETT, 2003), displays Earth-like morphologies that can only be explained by persistent fluvial activity. Paleomeander bend topography (fig. 2) shows that these were laterally accreting, alluvial rivers of a similar type to the modern Mississippi.

Although the relatively intense erosion phase terminated by the end of the heavy bombardment, immense volumes of water were episodically released from the Mars subsurface through outflow channels during subsequent Martian history (BAKER *et alii*, 1991). The water was delivered to the northern plains, where phenomenal topographic smoothness is consistent with the sedimentation (HEAD *et alii*, 1999).

4.6. PALEOHYDROLOGICAL HISTORY

As recognized early in the era of spacecraft exploration, channels and valleys extensively dissect the surface of Mars. Channels are elongated troughs that display clear evidence for large-scale fluid flow across their floors and on parts of their walls or banks. Immense channels, with widths of tens of kilometers and lengths of up to a few thousand kilometers, display a suite of morphological attributes that are most consistent with genesis by cataclysmic flows of water and sediment (BAKER, 2001).

Morphological evidence for past large bodies of water covering the northern plains of Mars, apparent by the late 1980s, includes the morphological characteristics of sedimentary deposits, and, more dramatically, a pattern of surrounding shorelines (CLIFFORD & PARKER, 2001). Evidence for the latter was systematically criticized in a global sense (CARR & HEAD, 2003), but supported for local areas by very detailed mapping (e.g., WEBB, 2004). Nevertheless, the general concept of past inundations on the northern plains, constituting an «Oceanus Borealis,» at least for geologically short episodes, has been found to be generally consistent with considerable geomophological evidence. The distinctive water-lain sedimentary deposits that cover parts of the Northern Plains, known as the Vastitas Borealis Formation, affords the most convincing case (CARR & HEAD, 2003), including (1) margins that roughly mark the surface to which a body of water would approximate, (2) a distinctive population of impact craters indicating associated ice and sediments (BOYCE *et alii*, 2005), and (3) a phenomenally flat and smooth surface expression, similar to that of abyssal plains in Earth's ocean basins.

The water body associated with emplacement of the Vastitas Borealis formation was approximately contemporaneous with the floods responsible for the largest outflow channels, and it may have covered as much as 30 million km^2 to average depths of hundreds of meters. The largest estimates involve as much as 30 million km^3 of water, equivalent to 200 meters spread evenly over the whole planet, and comparable to the inferred collective flows from the outflow channels (CARR & HEAD, 2003; BOYCE *et alii*, 2005), as proposed by BAKER *et alii* (1991). Other periods of outflow channel activity and associated inundations of the northern plains (CLIFFORD & PARKER, 2001; FAIREN *et alii*, 2003) are far less certain as to extent, relative timings, and durations of various inundation episodes. It was these various outflow events that distributed much of the surface type 2 materials («andesites») over the northern plains, as noted above.

What happened to the huge water inventory necessary for generating channelized megafloods and relatively short-lived lakes and seas? While a variety of atmospheric loss processes undoubtedly occurred, the geomorphological evidence suggests that water, even the «Oceanus Borealis», was not on the surface for prolonged periods. Instead it resided nearly all the time, except for brief, sometimes spectacular episodes, within, or beneath a semi-permanent, ice-rich permafrost. The long-term existence of this ice-rich layer, constituting a cryolithosphere about 1-2 km thick in equatorial areas and 5-6 km thick at the poles, is documented by a variety of geomorphological features (KUZMIN, 2005). Most of these have been well known since the 1970s, including various types of flow-lobed ejecta blankets (rampart craters), debris flows, lobate debris aprons, and polygonal terrains. A variety of landforms related to volcano-ice interactions (e.g., CHAPMAN *et alii*, 2000) document the occasional short periods of volcanically induced water outbursts from this reservoir of ice and underlying ground water. Following these episodes, surface water seems to have very rapidly returned to cryolithosphere. Thus, despite considerable theorizing (reviewed by CARR, 1996), a clear indication of the size of Mars' mostly hidden global water inventory cannot be gleaned from the isotopic composition of the tiny fraction of that inventory which was subject to long-term exospheric escape processes.

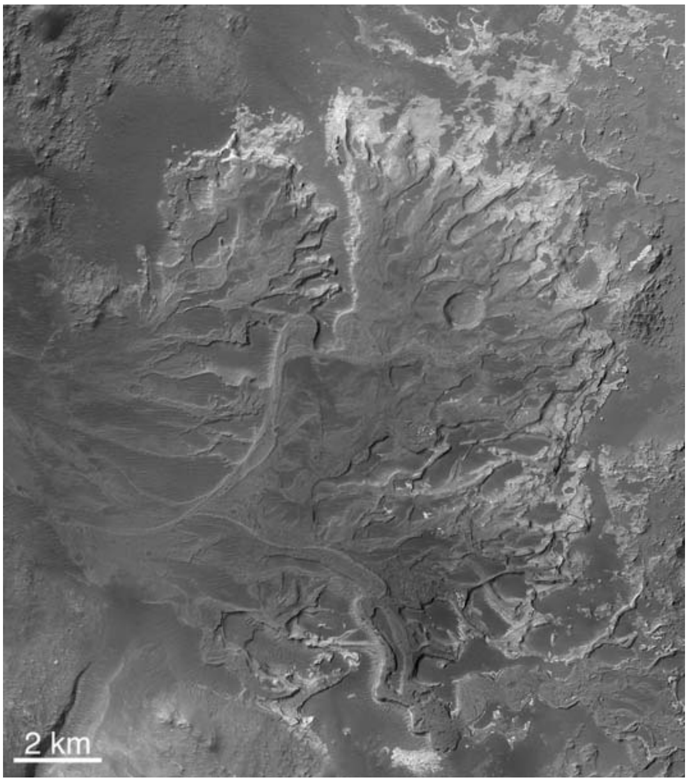

Fig. 2 - Distributary complex of alluvial channels in the crater Eberswald. The channel sediments, presumably sand and/or gravel, are etched into positive relief because of the erosional removal of adjacent materials, presumably overbank silt and/or clay. Note the prominent scroll bar topography associated with the meander bend near the center of the image.
– *Sistema di canali alluvionali nel cratere di Eberswald. I sedimenti del canale, presumibilmente sabbie e/o ghiaie, risaltano in rilievo positivo a causa dell'erosione dei depositi adiacenti, costituiti presumibilmente da silt e/o argille. Notare l'evidente topografia associata alla curva di meandro vicina al centro dell'immagine.*

4.7. THARSIS HISTORY

The Tharsis rise is an immense topographic dome, about 5000 km in diameter, situated along the equator and astride the planetary dichotomy between northern plains and southern highlands, and for which a plume origin has been proposed on geological grounds (MEGE & MASSON, 1996). A major phase transition at the base of the Martian mantle has been proposed as the key to initiating a single, stable plume beneath Tharsis (HARDER & CHRISTENSEN, 1996). However, this mechanism fails to account for the remarkable apparent stability of the plume, its specific location, and its persistence in time, long after the apparent reduced heat flow from the core that is indicated by the early cessation of the dynamo. Volcanism and tectonism became concentrated at Tharsis and Elysium, episodically operating through most of Martian history, extending from the later Noachian to the present (ANDERSON *et alii*, 2001; FAIREN *et alii*, 2003).

4.8. YOUNG WATER-RELATED ACTIVITY

Recent discoveries from Mars Orbiter Camera (MOC) images show that Mars displays a diverse suite of exceptionally young, globally distributed landforms that are water-related. If observed on Earth these landforms would generally be well understood to have aqueous origins, involving dynamical hydrological cycling on relatively short time scales (hundreds to thousands of years) in warmer, wetter, and denser atmosphere than occurs on Mars today. Among the young water-related landforms are numerous small gullies developed on hillslopes associated with crater rims and channel or valley walls. Morphological similarities of these hillslope gullies to terrestrial high-latitude, periglacial gullies suggests an origin by aqueous debris flows, involving the melting of near-surface ground ice. The gullies are uncratered, and their associated debris-flow fan deposits are superimposed on both eolian bedforms (dunes or wind ripples) and polygonally patterned ground, all of which cover extensive areas that are also uncratered (MALIN & EDGETT, 2000). The patterned ground is itself a very strong indicator of near-surface, ice-related processes in the active (seasonally thawed) layer above the Martian permafrost zone (SIEBERT & KARGEL, 2001).

Glaciated landscapes are some of the most important landform features to be documented with the newer high-resolution data. Earlier arguments for extensive glaciation on Mars were severely criticized, in part because glaciation has immense hydrological and climatological implications. The growth and persistence of large glaciers requires a dynamic hydrological system that moves large quantities of water from surface-water reservoirs, such as lakes and seas, through the atmosphere to sites of precipitation. The new evidence of glaciation is distinguished by its abundance, the complex detail of its assemblages, and the commonly very young geological ages (KARGEL, 2004).

5. GEOMARS

How has Mars been able to retain the potential, when an episode is initiated, to be hydrologically active right up to the present day? The GEOMARS theory `attempts to bring such anomalous observations together in terms of a model that is stimulated by understanding of the early history of Earth. As a working hypothesis the intention is not to provide a final picture, but instead to point of productive lines of inquiry toward concepts closer to the «true» representation.

5.1. PRELIMINARY MODEL FORMULATION

As a purely theoretical matter, Earthlike planets should evolve through progressive dynamical stages, including accretion, and tectonism (KAULA, 1975), and through various modes of mantle convention, including magma ocean, plate tectonic, and stagnant lid processes (SLEEP, 2000). For example, the surface of Earth has been largely controlled by plate tectonic processes, with associated plume activity, over the 3.9 Gyr of its history that is preserved in terrestrial rocks (CONDIE, 2005). Similar processes may also explain the geophysical character and geological history of Mars. This reasoning led to a previous model that invoked plate-tectonic processes to explain the origin of the highlands/lowlands topographic dichotomy on Mars (SLEEP, 1994). Sleep's model was sharply criticized by the Mars scientific community (e.g., NIMMO & TANAKA, 2005), and the GEOMARS hypothesis does not follow the geological aspects of Sleep's model. Nevertheless, the quantitative implications of the analysis (SLEEP, 1994) are taken as applicable in a different geological context to that of the original, specifically that of earliest Martian history, just prior to the late heavy bombardment (Age Model B, described above).

Building upon critical insights gained from study of data from recent planetary missions, the new geological theory invokes Earth-like volcanism and tectonics, combined with volatile release and sequestering, processes that were exceptionally intense very early in Martian history. It will first be very briefly described, and subsequent sections will elaborate upon various aspects to be developed by the proposed project.

The initial inventory and subsequent evolution of water on Mars begins with the nature of the solar nebula disk during planetary accretion. A dry scenario involves a relatively hot disk such that hydration cannot occur for planetessimals in the region of the present terrestrial planets. For this scenario, water is subsequently supplied to the inner solar system when perturbations by the giant planets, mainly Jupiter and Saturn, inject water-rich planetary embryos inward from the outer solar system. In contrast, a wet scenario begins with a cooler solar nebula and hydrated planetessimals in the region of Earth and Mars. The evidence of abundant water in Martian history, noted above, favors initial accretion from water-rich planetesimals (DRAKE & RICHTER, 2002). Mars then differentiated very rapidly, within a few tens of millions of years (HALLIDAY *et alii*, 2001), to form a liquid metallic core and solid mantle (STEVENSON, 2001). The smaller size of Mars relative to Earth (fig. 3) is very important for the rate of heat loss and subsequent evolution of the planet.

Mars' planet-forming process processes would have rapidly generated a steam atmosphere, rich in CO_2 and H_2O (ABE, 1997). The magma ocean between the hot planetary interior and the steam atmosphere would then develop a solid crust. As the planet and its atmosphere cooled, the latter would condense over the crust to form a planet-wide ocean of water. This juxtaposition of a global ocean over a very hot proto-lithosphere is ideal for the initiation of subduction, thereby initiating the process of plate tectonics. The young crust under the primordial ocean was easily hydrated (REESE *et alii*, 1998), promoting subduction because of a hydrosoftening process through water lubrication (REGENAUER-LIEB, 2001). The very rapid thermal evolution of Mars, in comparison to Earth, further promoted this transition from magma ocean to plate tectonics (SLEEP, 2000).

The very early phase of plate tectonics (PT) on Mars would have the following attributes, all of which will be further elaborated upon subsequently in this paper: (*a*) PT was a natural consequence of the progressive decline in heat flow (SLEEP, 2000) (fig. 4) and the evolution of the core (NIMMO & STEVENSON, 2000). (*b*) It occurred during the early part of the extremely intense heavy bombardment, not in later Martian history, as originally proposed by SLEEP (1994). (*c*) It was associated with an extremely strong core dynamo and consequent magnetosphere, leading to intensely magnetized oceanic plateaus that accreted to proto-continental terrains now in evidence as the linear anomalies of remnant magnetism in the Martian southern highlands (FAIREN *et alii*, 2002). (*d*) It conveyed, via subduction, water, carbon dioxide, and sulfates to the core-mantle boundary zone,

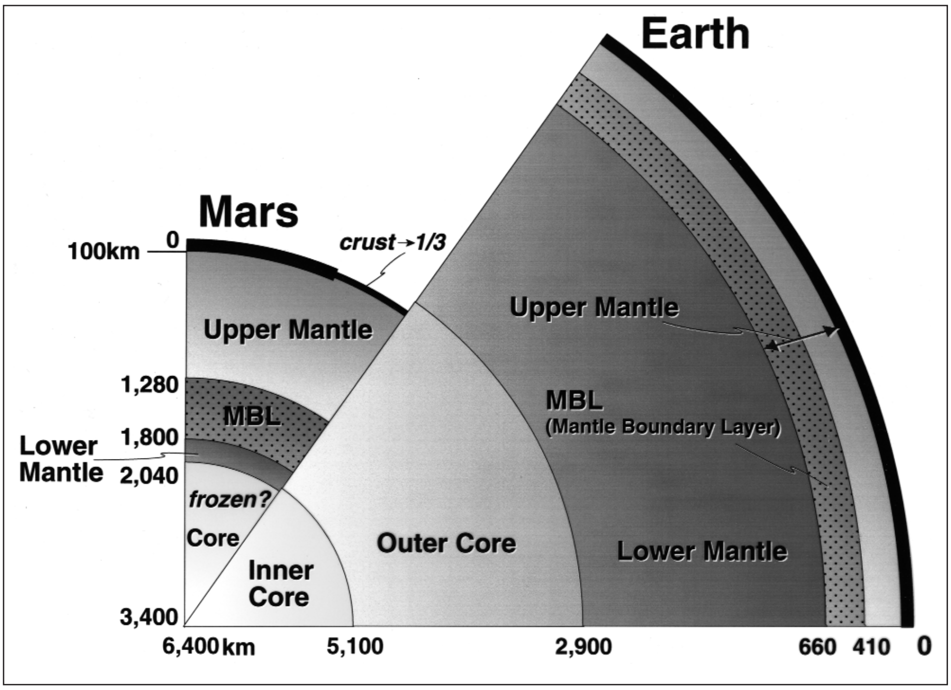

Fig. 3 - Comparison of internal planetary structures for Mars and Earth. Note that the lower part of the Martian upper mantle (a zone potentially rich in volatiles) lies very close to the mostly frozen Martian core.
– *Confronto tra le strutture planetarie interne di Marte e della Terra. Nota che la parte inferiore del mantello superiore di Marte (una zona potenzialmente ricca in volatili) si trova molto vicina al nucleo marziano per lo più congelato.*

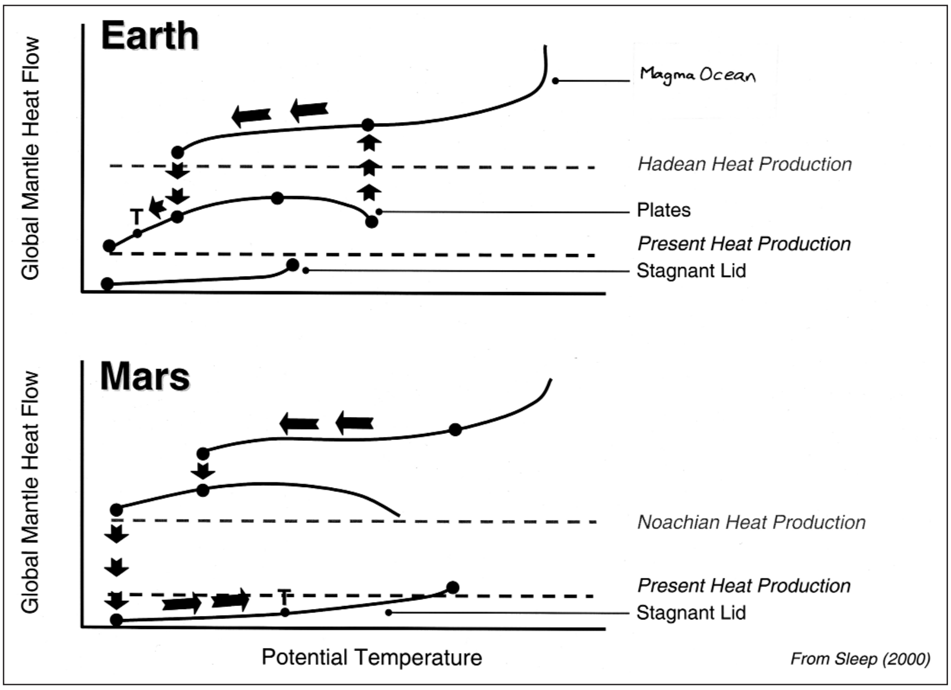

Fig. 4 - Comparison of hypothesized thermal evolutionary paths for Earth and Mars (Sleep, 2000).<
– *Confronto tra gli ipotetici tragitti dell'evoluzione termica della Terra e di Marte (Sleep, 2000).*

thereby depleting the reservoir of these materials from the surface to the upper mantle. (*e*) Its whole-mantle subduction processes cooled the evolving core, thereby terminating the dynamo during the heavy bombardment, prior to 4.0 Ga. (*f*) After at most a few 10^8 years, during which it generated the observed planetary dichotomy, PT ended with a phase of focused subduction, perhaps localized by late heavy bombardment mega-impact structures. The focused subduction led to the Tharsis superplume, with its massive late Noachian volcanism (Phillips *et alii*, 2001), with magmas derived from the hydrated zone of the lower mantle, in analogous manner to Earth-like superplumes (Maruyama, 1994). Episodic and long-term activity (decreasing in magnitude to the present day) are readily explained as direct consequences of the above scenario.

5.2. Heat Flow

Early studies of Martian thermal evolution utilized one-dimensional parameterized convection models, which give solutions for the average temperature as a function of depth (e.g., Schubert *et alii*, 1992). These studies depicted the general evolution of the thermal condition of Mars as follows: (1) A very hot early Mars undergoes substantial crustal differentiation within a few hundred Myr. The process of forming the crust by magmatism and volcanism removes heat-producing radiogenic elements from the mantle and concentrates them in the crust. (2) This leads to a significant depletion of heat sources in the mantle, which allows the mantle to cool more rapidly and thereby increase the lithosphere thickness. (3) The rest of the evolution is a steady decline of mantle temperature and thickening of the lithosphere to present values. This model seems reasonable given the small size of Mars compared to the Earth (JACKSON & POLLACK, 1984). In the later stages of Martian thermal evolution (stagnant lid convection regime), all heat lost from this system must necessarily be transported via conduction across the rigid lid. This would seem to suppress volcanism to minimal levels during the later stages of the Martian history. VAN THIENEN *et alii* (2004) add the modeling result that a more slowly cooling Mars may never have achieved a low enough potential temperature to allow PT, as implied by fig. 4. Instead, Mars would transition directly to the stagnant lid regime, where it resides today (REESE *et alii*, 1998).

Analysis of youngest martian meteorites reveals volcanic eruptions occurred within the last 100-200 Myr (NYQUIST *et alii*, 2001). Even younger volcanism is indicated by various geological studies (e.g., BERMAN & HARTMANN, 2002). These indications of long-lived Martian volcanism emphasize the need for a renewed consideration of Martian thermal evolution. The parameterized convection models, used in most thermal evolution studies, calculate one-dimensional temperatures as a function of depth. Volcanic events are usually inferred from arbitrary assumptions about the melt efficiency. Although this approach is appropriate enough to investigate the long-term overall melt productivity, it might be oversimplified as a means for understanding volcanic activity. Tharsis, for example, would be a region of volcanically thickened crust (e.g., SOLOMON & HEAD, 1982), but a hot mantle would definitely contribute to the observed topographic uplift. In the latter case, the plume(s) have warmer temperatures than the average mantle. Local decompression melting and lithospheric thinning above the upwelling convective flow will remain important, even into the very recent history of Mars (KIEFFER, 2003). Furthermore, as WILSON (2001) pointed out, the magma supply for the shield volcanoes from the mantle is episodic, rather than continuous. If we take these effects into account, the volcanic activities, especially recent examples, require a very different explanation than the popular model of static cooling via conduction across the stagnant lid.

5.3. Timing of PT

The period of Martian PT and associated rapid continental crustal accretion would have to occur in the first several hundred million years of Martian history (the earliest Noachian Epoch). This period was either a time of, or was immediately followed by, extensive erosion and formation of sediments, associated with a relatively dense, water-rich atmosphere. Cratering, erosion, and deposition of layered materials probably all occurred contemporaneously, leading to a complex interbedding of lava flows, igneous intrusions, sediments, buried craterforms, and erosional unconformities (MALIN & EDGETT, 2001). Add to this scenario the constructional process of continental accretion, plus the effects of large basin-forming impacts (Hellas and Argyre) during the late heavy bombardment (Age Model B), and one can explain key aspects of the highlands crustal thickness and magnetic anomaly patterns, as described below.

5.4. Core evolution and remnant crustal magnetism

If, as argued above, PT occurred on early Mars, the resulting high surface heat flux would lead to convection in the developing liquid core and the initiation of a dynamo (NIMMO & STEVENSON, 2000) (fig. 5). Additionally, there would be a spot-cooling effect produced by the impingement of subducted, hydrated slabs above the density-stratified molten core (middle diagram, fig. 5). This process will promote the growth of a solid inner core, and, because the solubility of light elements in solid iron decreases with increasing pressure (O'NEILL *et alii*, 1998), it will also drive chemical convection in the molten outer core (inset, fig. 5). Continued evolution of the core will then result in a remarkably strong dynamo and consequent magnetosphere, the latter providing a shielding effect in regard to the solar wind and high-energy particles from space.

Extremely rapid plate motion and subduction will result in (*a*) very fast accretion of thickened «continental» crust, and (*b*) removal of the ocean water to the mantle boundary layer over the cooling and solidifying core. Unusually large oceanic plateaus, generated over local mantle plumes, will also be accreted to the evolving Mars «continent», or «continents». The rocks in these assemblages are highly susceptible to very strong remnant magnetization. The presence of single-domain magnetite crystals in Martian meteorite ALH84001 (WEISS *et alii*, 2001) provides an important indicator of mineralization appropriate to very strong remnant magnetization. Very strong remnant magnetism is also reported from Icelandic basalts (KRISTHANNSON & JOHANESSON, 1999). Their incorporation into the accreting continental terrains would result in the observed prominent magnetic anomalies of the Martian highlands. The accretion process would insure that magnetization extended to such crustal depths that the late heavy bombardment would only be able to erase the signatures when extremely large impact basins formed, e.g., Hellas and Argyre.

Continued planetary cooling and core solidification terminated the dynamo while plate tectonics continued (right diagram, fig. 5), as predicted by the ultrahigh-pressure experiments on the Fe-FeO-FeS system at the core-mantle boundary pressure of 28 Gpa (BOEHLER, 1996). The continuing of PT after the termination of the dynamo resulted in the generation of northern plains oceanic crust that was not magnetized. Indeed, this last remnant of oceanic crust, the area now beneath the northern plains, shows no magnetic lineations (CONNERNY *et alii*, 1999), but it is marked by impact basins that were likely emplaced during the later part of the heavy bombardment (FREY *et alii*, 2002). This implies a temporal sequence such that PT ceased during the heavy bombardment, but the dynamo ceased earlier than that, but after the formation of bulk of the highlands crust.

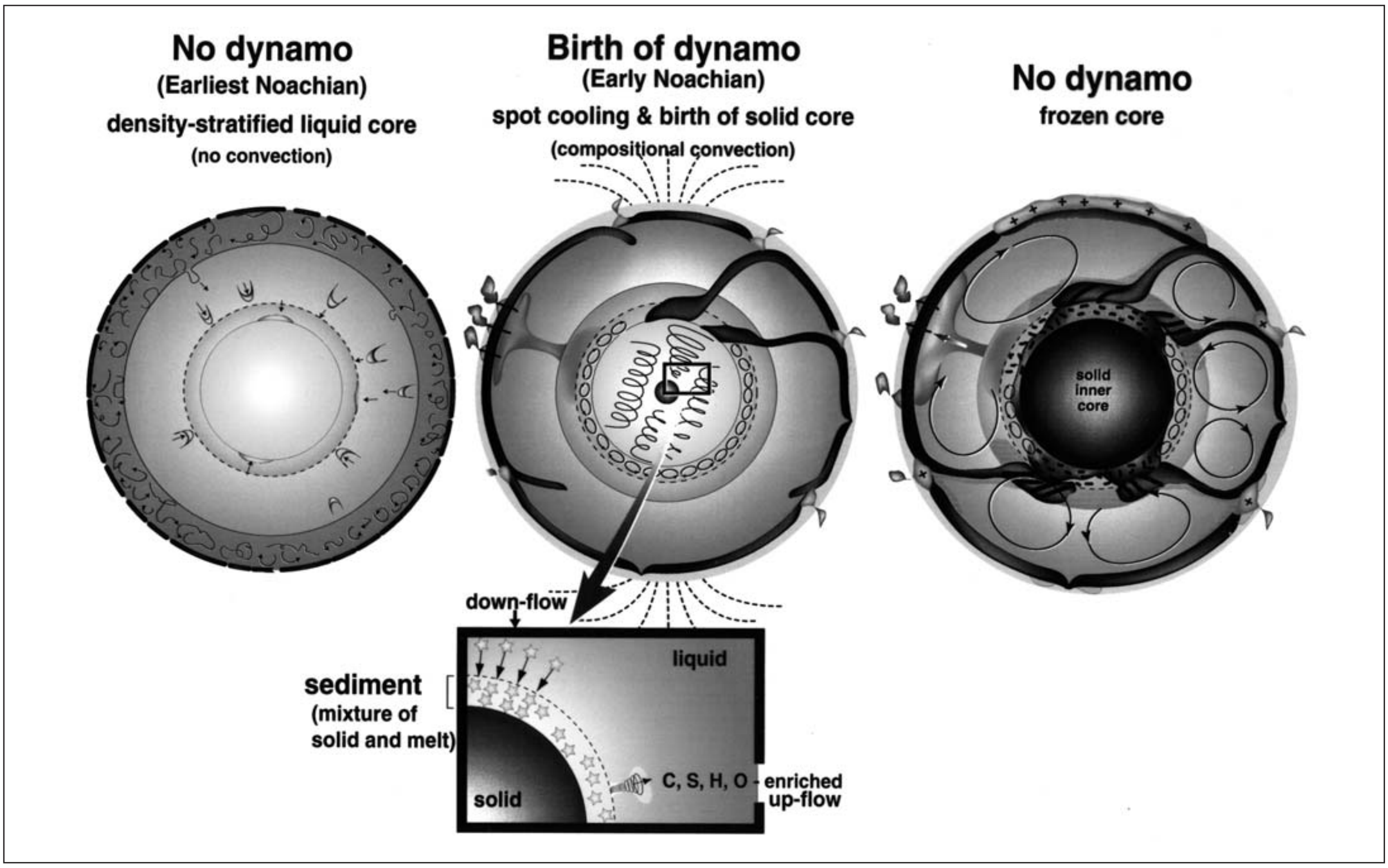

Fig. 5 - Hypothetical evolution of the Martian core and dynamo, according to the GEOMARS hypothesis. During the earliest Noachian (left), the core is liquid and density stratified. Mars is then in the magma ocean phase of heat release through the mantle (fig. 3). The dynamo is initiated (middle diagram) when subduction brings the relative cool plate slabs to the core-mantle-boundary (CMB) region (NIMMO & STEVENSON, 2000). The inset detail shows how siderophile elements (stars) move to the lowermost portions of the fluid core, thereby promoting chemical convection as light elements (C, S, H, O) are expelled from the solidifying inner core. This sets up the dynamo that continues operation until the inner core grows large enough that the remaining convection can no longer sustain the dynamo.
– Ipotetica evoluzione del nucleo e della dinamo di Marte, in accordo con l'ipotesi GEOMARS. Durante il Noachiano basale (a sinistra), il nucleo è liquido e stratificato secondo la densità. Marte è in questo caso nella fase di magma oceanico a causa del calore rilasciato attraverso il mantello (fig. 3). La dinamo è iniziata (diagramma centrale) quando la subduzione porta gli slab relativamente freddi al limite della regione nucleo-mantello (CMB) (NIMMO & STEVENSON, 2000). Il riquadro sottostante mostra come gli elementi siderofilici (stelle) si muovano verso la porzione più inferiore del nucleo fluido, generando in tal modo convezione chimica in quanto gli elementi leggeri (C, S, H, O) vengono espulsi dal nucleo interno in solidificazione. Tale fenomeno dà origine alla dinamo che continua l'operazione finché il nucleo interno cresce in modo tale che la convezione rimanente non è più in grado di sostenere la dinamo.

5.5. SUBDUCTION OF VOLATILES

N. Sleep (SLEEP, 1994) showed that, in comparison to Earth and for similar thermal conditions, reduced Martian gravity (0.3795 that of Earth) results in the following: (1) Martian oceanic crust produced in sea-floor spreading will be considerably thicker; (2) it will spread much more rapidly; and (3) the hydrothermally altered zone of oceanic crust on Mars will be much thicker (SLEEP, 1994). Thus, the combination of mid-oceanic rifting, relatively rapid sea-floor spreading, and efficient subduction will be especially effective at injecting hydrothermally emplaced water, carbonates, and sulfates of the upper oceanic crust into the Martian mantle (KITAJIMA *et alii*, 2001). If PT was indeed present on early Mars, subduction of a thick carbonate layer formed by ridge hydrothermal metamorphism would transport CO_2 into the mantle, thereby sequestering the CO_2 that otherwise would comprise carbonate rocks. The subduction of hydrated lithosphere will lead to dehydration reactions that lower melting temperatures in the portions of the asthenosphere lying above the subducting slab. As on Earth (CAMPBELL & TAYLOR, 1983), this process will generate calc-alkaline rocks, including andesites. In our conceptual model these silicic rocks are initially associated with arc volcanism, and their deep-seated plutonic equivalents are granite. As noted above, both granite and andesite have been discovered on Mars, though not generally explained in the manner noted here.

5.6. THARSIS SUPERPLUME

The long-standing geophysical problem of the long-wavelength elevated topography at Tharsis seems now to be resolved in favor of volcanic construction on the lithosphere (ZHONG & ROBERTS, 2003). Massive volumes of flood basalt were emplaced in the late Noachian (PHILLIPS *et alii*, 2001), perhaps with temporary dynamical support from a rising plume head (HARDER & CHRISTENSEN, 1996). What is remarkable and largely unexplained, however, is the long-continuing activity of

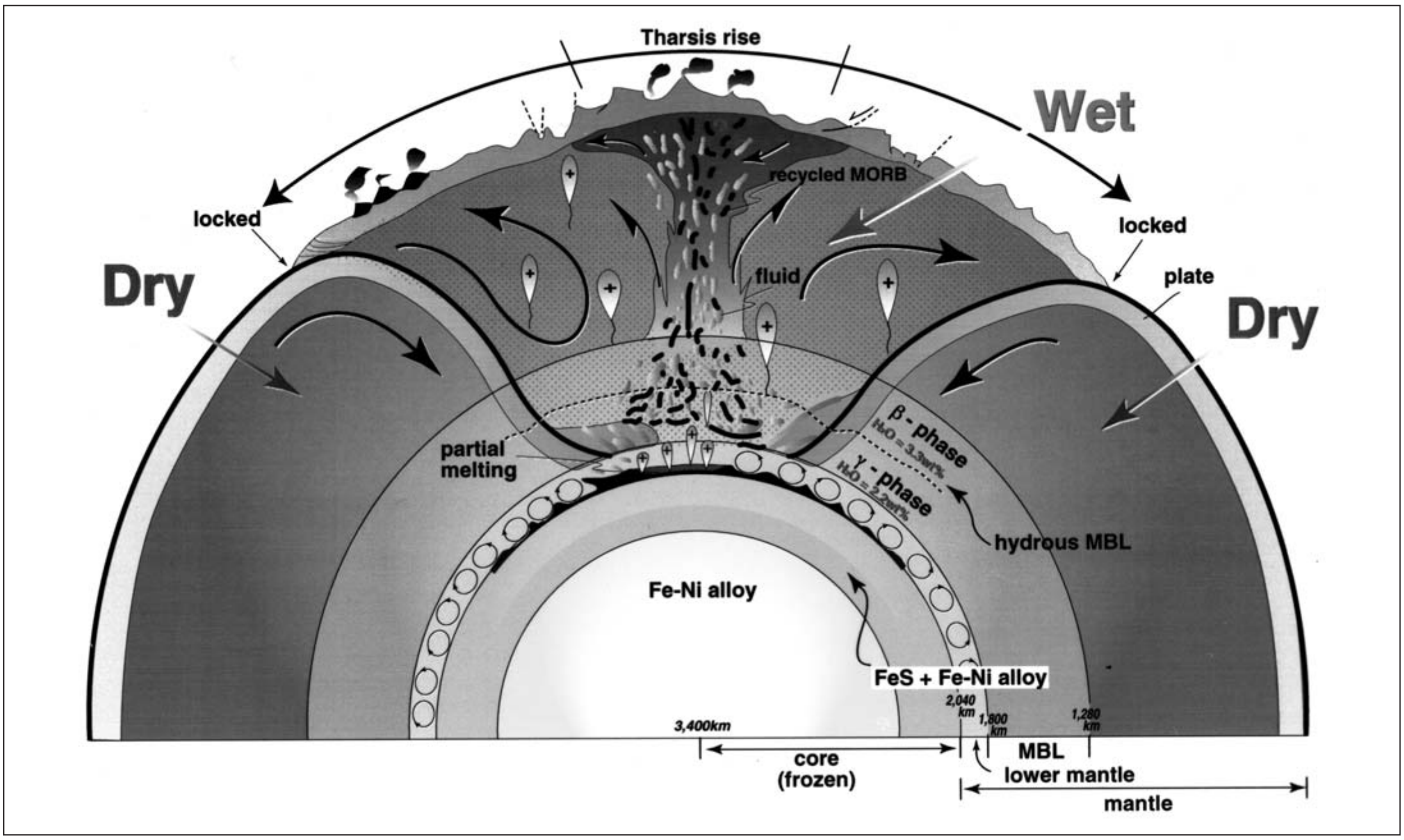

Fig. 6 - Hypothetical initiation of the Tharsis superplume by focused subduction. Partial Melting of volatile-rich material in the mantle boundary layer (MBL) generates the Huge upwelling of magma and associated outgassing that occurred during the Initiation of the Tharsis rise (PHILLIPS *et alii*, 2001). Subsequent outburst flooding (BAKER *et alii*, 1991) is generated by the continuing volcanic and tectonic activity, thereby promoting brief episodes of climate change, i.e., the MEGAOUTFLO theory.
– *Ipotetica fase di inizio del superpennacchio di Tharsis innescato dalla subduzione focalizzata. La fusione parziale del materiale ricco in volatili nello strato basale di mantello (MBL) genera l'immensa risalita di magma e l'associata degassazione che è avvenuta durante l'inizio della risalita del Tharsis (PHILLIPS* et alii, *2001). La seguente inondazione repentina (BAKER* et alii, *1991) è generata dalla prosecuzione dell'attività vulcanica e tettonica, che quindi innesca brevi episodi di cambiamento climatico (vedi la teoria dei MEGAOUTFLO).*

Tharsis, both volcanic and tectonic (ANDERSON *et alii*, 2001; FAIREN & DOHM, 2004). Is it a sufficient explanation to invoke the continuing, though diminishing mantle heat source for maintaining such a plume (e.g., SPOHN *et alii*, 2001)? The time scale is about 4 Gyr.

Some time after the cutoff of the core dynamo, PT terminated on the cooled Mars, perhaps about 4 billion years ago. It would have been replaced by stagnant lid convection and associated episodic plume activity on a one-plate planet. Water, carbonates, and sulfates had by then been largely conveyed to the mantle boundary layer, immediately above the more slowly cooling solid core. The surface was now cold and dry, but the seeds of its episodic transformation had been sown into the deep mantle. The water-rich lower mantle decreased melting temperatures and viscosities above those preferential zones most enriched in water. These zones had been pre-established by processes associated with the termination of plate tectonics, as noted above, during the late heavy bombardment. The latter would have been highly disruptive to the organized nature of the PT process. It could have generated superplumes at Tharsis and Elysium by either or both of the following processes: (1) giant impacts (REESE *et alii*, 2002), or (2) focused subduction. The latter might operate by double-sided convection (fig. 6). The conductive heating from the underlying core would have led to breakdown reactions of hydrous beta and gamma mineral phases to liberate free water in hydrous plumes. The recycled MORB crusts within the plumes became a potential source of flood basalts, and, by their heterogeneous distribution, they caused episodic magma ascent and volcanism. Moreover, the presence of a lower mantle on Mars may have acted as a thermal boundary layer to further induce episodicity of Tharsis magmatism.

Collectively, the above-described phenomena constitute the Tharsis superplume (fig. 6) initially leading to immense outpourings of basaltic lava during the late Noachian (PHILLIPS *et alii*, 2001). At declining rates, lavas continued to emerge throughout Martian history. Further evidence for this scenario is found in the SNC Martian meteorites most of which represent basalts with crystallization ages between 0.15 and 1.3 Ga (NYQUIST *et alii*, 2001). These basalts derived from magmas that were water-rich (MCSWEEN *et alii*, 2001). Moreover, their oxidized state relative to the ancient, primordial Mars sample provided by meteorite ALH84001 (WARREN & KALLEMEYN, 1996) may indicate derivation from a relatively hydrous, recycled source region, as would be expected in this scenario.

Beginning in the later Noachian, the magma-driven structural landform complexes of the Tharsis superplume became the sites of immense outflows of water. Possibly associated with the downwelling of the subducting plates, a huge sedimentary basin developed at Tharsis during its early history (DOHM *et alii*, 2001). This would have been analogous in timing and association to the megabasins characterizing the early development of terrestrial superplumes (MARUYAMA, 1994; IRVINE, 1989). Also similar to Earth, parts of the Tharsis basin were subsequently inverted by magmatic-driven uplifts (DOHM *et alii*, 1998; ANDERSON *et alii*, 2001), probably related to later upwelling of the superplume. The formation of Valles Marineris exposed the 10-km thick pile of lavas (MCEWEN *et alii*, 1999), and probable interfingering sediments (MALIN & EDGETT, 2001), that comprise the fill of the ancient basin.

The outburst floods eroded into the deep andesitic crust of the highlands, delivering the resulting sediments to blanket the oceanic crust of the northern lowlands with a thin andesitic cover, while the highlands were mantled by the products of younger, plume-related basaltic lavas, thereby explaining the observed surface compositions (BANDFIELD *et alii*, 2000). Although considerable CO_2, H_2O and SO_2 were temporarily delivered to the atmosphere in episodic outbursts (BAKER *et alii*, 1991), these were subsequently trapped in the near-surface permafrost zone as ground ice and gas hydrates (BAKER, 2001). The episodes of climate change were sufficiently infrequent and of such short duration to have not produced appreciable weathering of basalt rock outcrops. Any remaining atmosphere was progressively altered by the long-term action of the solar wind, unconstrained by effects of a magnetosphere.

Volatile-rich magmas (MCSWEEN *et alii*, 2001) that emerged during post-PT, post-heavy-bombardment Martian history were probably derived from the deep-mantle reservoir that had been charged by very early subduction processes. In later Mars history, water delivered to the surface by volcanism eventually concentrated as ground ice and ground water in the near-surface crust, where it is still present (BOYNTON *et alii*, 2002). This water was episodically returned to the surface by outflow channel activity and valleys (BAKER *et alii*, 1991), as outlined in the MEGAOUTFLO theory (BAKER *et alii*, 2000; FAIREN *et alii*, 2003). The various channels are cut into the deeper silicic crust of the highlands, which was partly derived from ancient PT- accretionary processes (FAIREN *et alii*, 2002). The silicic sediments were delivered to the northern plains, while the highlands and Tharsis became mantled by relatively young, volatile-poor basalts, derived from the more depleted upper mantle. The Martian surface has remained essentially cold and dry since at least the late Noachian, but its very recent water-related episode and past episodes reflect short-term excursions that can be explained as natural consequences of the ancient legacy of a very early aqueous history and associated plate tectonics.

6. DISCUSSION

The foregoing holds that Mars, like Earth, is characterized by long-term cycles of water and rock (igneous, metamorphic, and sedimentary). These cyclic processes are intimately tied to the evolution of the planetary lithosphere, atmosphere, and hydrosphere. However, the thermal evolution of Mars was much faster than that of Earth. Mars experienced and completed its plate-tectonic phase during the 400 to 500 Myr period prior to the late heavy bombardment (Age Model B), while Earth remains in the plate tectonics evolutionary phase (fig. 4). Thus, the theory strongly follows the insight (SLEEP, 1994) that the phenomenon of plate tectonics is not exhausted by a planetary sample of one, but rather that it is a natural consequence of the more general evolutionary sequence of a water-rich terrestrial planet.

Mars formed its highlands/lowlands dichotomy, as Earth did, but it did so much more rapidly, and in the time interval between the end of its magma ocean and the disruption of the late heavy bombardment. It was the latter that terminated plate tectonics, but it was also the latter that established the transition to the persistent superplume activity at Tharsis and Elysium. The hydrated lithosphere that was subducted to the Martian interior by its early plate-tectonic phase provides the reservoir that sustained the episodic hydrological activity through later Martian history that so clearly contradicts the MIDDEN hypothesis.

ACKNOWLEDGEMENTS

The author thanks Forese Wezel for his encouragement in regard to submitting this paper. The GEOMARS model was developed in close collaboration with Shigenori Maruyama and James Dohm. Comments (but not necessarily agreement) from Norm Sleep aided in clarifying points in the argument. Shio Wantanabe assisted with the design and preparation of the figures.

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Manoscritto pervenuto il 00 .... 2006; testo approvato per la stampa il 00 .... 2006; ultime bozze restituite il 00 .... 2006.