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Megafloods and global paleoenvironmental change on Mars and Earth

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ABSTRACT

The surface of Mars preserves landforms associated with the largest known water floods. While most of these megafloods occurred more than 1 Ga ago, recent spacecraft images document a phase of outburst flooding and associated volcanism that seems no older than tens of millions of years. The megafloods that formed the Martian outflow channels had maximum discharges comparable to those of Earth's ocean currents and its thermohaline circulation. On both Earth and Mars, abrupt and episodic operations of these megascale processes have been major factors in global climatic change. On relatively short time scales, by their influence on oceanic circulation, Earth's Pleistocene megafloods probably (1) induced the Younger Dryas cooling of 12.8 ka ago, and (2) initiated the Bond cycles of ocean-climate oscillation with their associated Heinrich events of "iceberg armadas" into the North Atlantic. The Martian megafloods are hypothesized to have induced the episodic formation of a northern plains "ocean," which, with contemporaneous volcanism, led to relatively brief periods of enhanced hydrological cycling on the land surface (the "MEGAOUTFLO Hypothesis"). This process of episodic short-duration climate change on Mars, operating at intervals of hundreds of millions of years, has parallels in the Neoproterozoic glaciation of Earth (the "Snowball Earth Hypothesis"). Both phenomena are theorized to involve abrupt and spectacular planet-wide climate oscillations, and associated feedbacks with ocean circulation, land-surface weathering, glaciation, and atmospheric carbon dioxide. The critical factors for megascale environmental change on both Mars and Earth seem to be associated tectonics and volcanism, plus the abundance of water for planetary cycling. Some of the most important events in planetary history, including those of the biosphere, seem to be tied to cataclysmic episodes of massive hydrological change.

INTRODUCTION

Earth and Mars are the only two planets known to have geological histories involving vigorous surface cycling of water between reservoirs of ice, liquid, and vapor. Although the current state of the Martian surface is exceedingly cold and dry, there are extensive reservoirs of polar ice and ground ice (Boynton et al., 2002), plus probable immense quantities of groundwater beneath an ice-rich permafrost zone (Clifford, 1993; Clifford and Parker, 2001). Results from recent spacecraft missions have generally corroborated a theory, first presented by Baker et al. (1991), that periodically Mars' cold, dry, stable state has been perturbed by massive outbursts of water and gas, leading to a cool, wet atmosphere in contact with standing bodies of water (lakes, seas, or even a temporary "ocean"). Labeled "the episodic ocean hypothesis" by Carr (1996), the Baker et al. (1991) theory was initially considered to be outrageous (Kerr, 1993). The prevailing theoretical view of Mars until relatively recently has been that Mars Is

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continuously Dead and Dry Except during the Noachian (MIDDEN). (The Noachian is the "early Mars" epoch, extending from 4.5 to ~3.8 Ga ago). The MIDDEN hypothesis is finally being recognized as inconsistent with numerous important aspects of Martian geology, including extensive evidence for very recent water-related landforms (e.g., Baker, 2001, 2004, 2005). In light of the new evidence, the original Baker et al. (1991) hypothesis has been regenerated as MEGAOUTFLO: "Mars Episodic Glacial Atmospheric Oceanic Upwelling by Thermotectonic FLood Outburst" (Baker et al., 2000; see also, Kargel, 2004).

On Earth the oceans are integral to long-term climate change. Their currents distribute heat between the equator and the poles. For example, the Gulf Stream flows at discharges of up to 100 sverdrups (Sv), involving relatively slow moving water 1 km in depth and 50–75 km wide. (The sverdrup, equivalent to 1×10^6 m^3/s, is the unit of discharge for both ocean currents and megafloods.) As northward-flowing Atlantic Ocean seawater evaporates and becomes more saline, it increases in density, eventually sinking in the northern Atlantic. This process forms a portion of the great global thermohaline circulation pattern, which acts as a conveyor belt for heat in the oceans. However, this global-scale circulation pattern was disrupted during the last glaciation when megafloods (floods with peak discharges on the order of a Sv or more) introduced relatively low-density, freshwater lids over large areas of ocean surface. The resulting disruption of sea-surface temperatures and density structure drastically altered the meridional transport of heat on a global scale. Earth's global climate was altered on time scales of decades to centuries (Broecker et al., 1989; Barber et al., 1999). Thus both Earth and Mars have aspects of their long-term hydrological cycles that involve the cataclysmic-flood triggering of major epochs of global paleoenvironmental change.

MEGAFLOODS

High-energy megafloods are planetary-scale phenomena, associated with glacier outburst settings, glacial lake spillways, and the immense outflow channels of Mars (Baker, 2002). Paleohydraulic analyses of these floods show that their peak discharges can be comparable to those of ocean currents (Table 1). Collectively, discharges from all the Martian outflow channels may have totaled as much as 100–1000 Sv (Baker et al., 1991). These values imply total released reservoir volumes of 10^5–10^7 km^3 of water, using scaling relationships for terrestrial superfloods (Baker et al., 1993). The higher volumes from these preliminary calculations match the volume of water estimated from Martian topography to have ponded on the surface of the planet, mainly in a temporary "ocean" on its northern plains (Parker et al., 1993; Head et al., 1999).

Martian Outburst Flooding

The Martian outflow channels involve the immense upwelling of cataclysmic flood flows from subsurface sources (Baker and Milton, 1974), mostly during later periods of Martian history, after termination of the heavy bombardment phase at ~3.9 Ga. The huge peak discharges implied by the size and morphology of the outflow channels (Baker et al., 1992) are explained by several models (Table 2). A popular view is that a warm, wet climate phase during the heavy bombardment was followed by a progressively thickening ice-rich permafrost zone during subsequent cold and dry Martian history. The outflow channels result from releases of subsurface water that was confined by this process (Carr 1979, 2000; Clifford and Parker 2001). Certainly, there is strong evidence, notably from impact crater morphologies (Carr 1996), that much of the Martian surface is underlain by a thick ice-rich permafrost zone, a "cryolithosphere" (Kuzmin et al. 1988). However, the geological record shows that volcano-ice-water interactions are commonly associated with outburst flood channels. Thus episodic heat flow and volcanism (Baker et al. 1991) affords an alternative to the linear model of progressive pressurization of confined water by cryosphere thickening. The MEGAOUTFLO hypothesis envisions long periods (perhaps on the order of 10^8 a) during 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 groundwater. The stable state is punctuated by relatively short-duration (perhaps 10^4 or 10^5 a) episodes of quasistable conditions that are warmer and wetter than those at present.

The energy for the immense outflow channel floods could have been supplied by the thermal and tectonic effects of immense mantle plumes. In this MEGAOUTFLO scenario, gas hydrate in the Martian permafrost zone is destabilized by episodes of very high heat flow (and associated volcanism), thereby releasing radiatively active gas from the lower permafrost zone (2 to 3 km depths). This process could involve carbon dioxide or methane (Kargel et al., 2000; Max and Clifford, 2001; Tanaka et al., 2001). The dissolved gas from the underlying groundwater and the gas released from ice in the permafrost zone would contribute to explosively pressurized slurries of water and sediments in massive outbursts (Komatsu et al., 2000). In the atmosphere these radiatively active gases can generate a transient greenhouse that would coincide with the immense pondings of water produced by the outburst floods.

Exceptionally young outflow channels and associated volcanism occur in both the Cerberus plains and the Tharsis regions of Mars (Hartmann and Berman, 2000; Mouginis-Mark 1990; Tanaka et al., 2005). Data from the Mars Global Surveyor (MGS) show that localized water releases, interspersed with lava flows, occurred approximately within the last 10 Ma (Berman and Hartmann 2002, Burr et al. 2002). The huge discharges associated with these floods and the temporally related volcanism should have introduced considerable water into active hydrological circulation on Mars. The remarkable evidence for very recent outburst floods (Burr et al., 2002) suggests that a relatively small MEGAOUTFLO episode occurred recently on Mars. Evidence for extensive sulfate salts on the Martian surface (Paige, 2005) is also consistent with this model, in that the SO_2 and water generated from

TABLE 1. PROPERTIES OF VARIOUS MEGAFLOODS AND MEGAFLOWS

Location	Width (km)	Depth (m)	Velocity (m/s)	Discharge (Sv)	References
Missoula Flood (Rathdrum)	6	150	22	20	Baker (1973); O'Connor and Baker (1992)
Altai Flood (Central Asia)	2.5	400	25	20	Baker et al. (1993)
Maadim Vallis (Mars)	5	100	10	5	Irwin et al. (2004)
Mangala Vallis (Mars)	14	100	15	20	Komar (1979)
Kasei Vallis (Mars)	83	374	32	1000	Robinson and Tanaka (1990)
Gulf Stream	50–75	1000	1–3	100	Gross (1987)

TABLE 2. MEGAFLOOD GENERATION (MARS)

Mechanism	Examples	References
Subice volcanism	Chryse Channels	Masursky et al. (1977); Chapman et al. (2003)
Lake spillways	Maadim Vallis	Irwin et al. (2004)
	Mangala Vallis	Zimbelman et al. (1992)
Hydrostatic pressure in large-scale confined aquifers	Chryse Channels	Carr (1979, 2000)
Liquefaction and mudflows	Ravi Vallis	Nummedal and Prior (1981)
Pressurized water release	Mangala Vallis	Tanaka and Chapman (1990)
From fractures, graben, dikes	Athabasca Vallis	Burr et al. (2002)
Decompression of CO	General	Hoffman (2000)
Decompression/melting of CO and expulsion of water	General	Milton (1974); Komatsu et al. (2000); Max and Clifford (2001)

TABLE 3. MEGAFLOOD GENERATION (EARTH)

Mechanism	Example	Discharge	References
Subglacial volcanism	Icelandic Jokulhlaups	0.1–1.0	Bjornsson (2002)
Lake spillways	Bonneville	1	O'Connor (1993)
	Strait of Dover	10	Smith (1985)
Ice-dammed lake failure	Missoula	10–20	O'Connor and Baker (1992)
	Altai	10–20	Baker et al. (1993); Herget (2005)
	Agassiz	0.3	Teller et al. (2002)
	Agassiz, Ojibway	5–10	Clarke et al. (2004)
Pressurized subglacial outburst	Livingstone Event (Laurentide Ice Sheet)	60	Shaw (1996)

the volcanism and flood outburst would have produced the acid conditions to generate extensive sulfate salt emplacement on the Martian surface. The recent MEGAOUTFLO episode may also have been a trigger for water migration, leading to ice emplacement (Baker, 2003) in latitudinal zonation for which orbital variations likely acted as the pacemaker (Head et al., 2003).

Terrestrial Glacial Floods

Some Earth megafloods also derive from ice-volcano interactions (Table 3). However, ice-marginal lakes are the sources of the largest, well-documented (and noncontroversial) glacial megafloods. Perhaps the most famous example is Glacial Lake Missoula, which formed south of the Cordilleran Ice Sheet, in the northwestern United States (Baker, 1973). The Purcell Lobe of the Ice Sheet extended south from British Columbia to the basin of modern Pend Oreille Lake in northern Idaho. It thereby impounded the Clark Fork River drainage to the east, forming Glacial Lake Missoula in western Montana. At maximum extent this ice-dammed lake held a water volume of ~2500 km^3 with a depth of 600 m at the dam. The lake covered 7500 km^2, and it held a volume of ~2500 km^3. Cataclysmic failure of the ice dam impounding this lake resulted in discharges up to ~20 Sv (O'Connor and Baker, 1992). On land these flows produced the distinctive erosional and depositional features of the Channeled Scabland, including scabland bedrock erosion, streamlining of residual uplands, large-scale scour around obstacles, depositional bars, giant current ripples, and huge sediment fans (Baker, 1981).

Upon reaching the Pacific Ocean the Missoula floodwaters continued flowing down the continental slope as hyperpycnally generated turbidity currents. The sediment-charged floodwaters followed the Cascadia submarine channel into and through the Blanco Fracture Zone and out onto the abyssal plain of the Pacific. As much as 5000 km^3 of sediment may have been carried and distributed as turbidites over a distance of 2000 km west of the Columbia River mouth (Normark and Reid, 2003).

The largest well-documented glacial megalake formed in north-central North America in association with the largest glacier of the last ice age, the Laurentide Ice Sheet. This ice sheet is known to have been highly unstable throughout much of its history. Not only did freshwater discharges from the glacier result in ice-marginal lakes; outbursts of meltwater into the Atlantic Ocean may have generated climate changes by influencing the thermohaline circulation of the North Atlantic Ocean (Teller et al., 2002). As the Laurentide Ice Sheet of central and eastern Canada retreated from its late Quaternary maximum extent, it was bounded to the south and west by immense meltwater lakes, which developed in the troughs that surrounded the ice. As the lake levels rose, water was released as great megafloods, which carved numerous spillways into the drainages of the Mississippi, St. Lawrence, and Mackenzie Rivers (Kehew and Teller, 1994). The greatest megafloods developed from the last of the ice-marginal lakes, a union between Lake Agassiz in south-central Canada and Lake Ojibway in northern Ontario. The resulting megalake held ~160,000 km^3 of water, which was released subglacially ~8200 a ago under the ice sheet and into Labrador Sea via the Hudson Strait (Clarke et al., 2004).

A Laurentide meltwater-discharge event around 13,350 yr B.P. used the Hudson River valley. This megaflood drained Glacial Lakes Iroquois, Vermont, and Albany by breaching a moraine dam at the Narrows in New York City. It also initiated a short-lived (<400 a) cold event by diminishing the thermohaline circulation (Donnelly et al., 2005). The common influence of terrestrial megafloods is to generate more glacial conditions than what was prevailing immediately prior to the flooding.

Lowland glacial lakes of Siberia involved the expansion of huge Quaternary ice sheets that covered the shallow seas north of Eurasia and blocked north-flowing rivers, notably the Ob, Irtysh, and the Yenesei. In the 1970s Mikhail G. Grosswald recognized that, as in North America, the resulting proglacial lakes were immense and involved important diversions of meltwater through huge spillways (Grosswald, 1980). In European Russia, water that previously flowed to the Arctic was instead conveyed to the south-flowing Dnieper and Volga Rivers. More importantly, the great north-flowing Siberian Rivers, the Irtysh, Ob, and Yenesei, emptied into a megalake, Lake Mansi, which drained southward through the Turgai divide of north-central Kazakhstan to the basin of the modern Aral Sea. The Aral, in turn, drained though a spillway at its southwestern end into the Caspian, which expanded to a Late Quaternary size over twice its modern extent, known as the Khvalyn paleolake. The Khvalyn paleolake spilled westward through the Manych spillway into the Don valley, then to the Sea of Azov, and through the Kerch Strait to the Euxine Abyssal Plain (the floor of the modern Black Sea). Then, disconnected from the Agean and filled by freshwater (the New Euxine phase), the glacial meltwater filled the Black Sea basin. This basin functioned in two modes during the Quaternary. Its cold-climate mode was a freshwater lake (that may have filled and drained through the northwestern Turkey to the Agean). Its warm-climate phase involved rising global sea level, inducing salt-water invasions through the Turkish straits to form the saline Black Sea, the last of which occurred ~8000 a ago, an inundation that may have inspired the story of Noah (Ryan et al., 2003).

Subglacial Megaflood Hypotheses

Over the past 20 a, a controversial theory has emerged for immense cataclysmic flooding beneath the continental ice sheets of the last terrestrial glaciation. As outlined by Shaw (1996) this theory derives from inferred origins for a variety of enigmatic subglacial landforms, involving water erosion and deposition. These landforms include drumlins (Shaw, 1983, 2002; Shaw et al., 1989), Rogen moraines (Fisher and Shaw, 1993), large-scale bedrock erosional flutings and streamlining (Kor et al., 1991), gravel sheets in eskers (Brennand and Shaw, 1994), hummocky terrain (Munro and Shaw, 1997), pendant bars (Sjogren and Rains, 1995), and tunnel channels (valleys) (Shaw, 1988). Though commonly explained by subglacial ice deformational processes and related, small-scale water flows, the genesis of these features cannot be observed in modern glaciers that are much smaller than their late Quaternary counterparts. Shaw (1996) explains the assemblage of landforms as part of an erosional/depositional sequence beneath continental ice sheets that precedes regional ice stagnation and esker formation with a phase of immense subglacial sheet floods, which, in turn, follows ice-sheet advances that terminate with surging, stagnation, and melt-out. Shaw (1996) proposes that peak discharges of tens of sverdrups are implied by the late Quaternary subglacial landscapes of the southern Laurentide Ice Sheet. Release volumes are also huge. Blanchon and Shaw (1995) propose that a 14 m sea-level rise at 15 ka resulted from such megaflooding.

Shoemaker (1995) provides some theoretical support for Shaw's model, though at smaller flow magnitude levels. Arguments against the genetic hypotheses for the landforms are given by Benn and Evans (1998). Walder (1994) criticizes the hydraulics, and Clarke et al. (2005) object that the theory requires unreasonably huge volumes of meltwater to be subglacially or supraglacially stored and then suddenly released.

Subglacial cataclysmic flooding has recently been proposed for the Mid-Miocene ice sheet that overrode the Transantarctic Mountains (Denton and Sugden, 2005). Spectacular scabland erosion occurs on plateau and mountain areas up to 2100 m in elevation, over an 80-km mountain front. The inferred high-energy flooding could have been supplied from subglacial lakes, such as modern Lake Vostok (Siegert, 2005). Such lakes would have formed beneath the thickest, warm-based portion of the ice sheet, located inland (west) of the mountains (Sugden and Denton, 2004). Thinner ice overlying the mountains was probably cold-based, thereby generating a seal that could be broken when the pressure of water in the lakes, confined by thick overlying ice, reached threshold values. The water from the lakes would move along the ice-rock interface, along the pressure gradient up and across the mountain rim. The high-velocity flooding would be further enhanced to catastrophic proportions as conduits were opened by frictional heat in the subglacial flows (Denton and Sugden, 2005).

Perhaps the most spectacular hypothesized subglacial flooding is Grosswald's (1999) proposal that much of central Russia was inundated in the late Quaternary by immense outbursts from the ice-sheet margins to the north. Using satellite imagery to map large-scale streamlined topography and flowlike lineations, Grosswald (1999) infers that the entire Arctic Ocean was confined beneath an ice sheet that grew from converging ice shelves, which coalesced from the ice sheets that formed on the northern margins of the surrounding continents. This water then broke out during the Pleistocene from a point in northwestern Siberia, flowing toward the Caspian and then to the Black Sea. The pathway is approximately similar to that of the Turgai and Manych Spillways, noted above. However, this hypothesis, which has some similarities to proposals for subglacial megaflooding, has not been adequately tested in the field.

GLOBAL CONSEQUENCES

Earth's Oceans

Earth's oceans constitute a vast, interconnected body of water that covers ~70% of the planet's surface. Moreover, this water body has persisted throughout at least the last 3.9 Ga of planetary history, acting as a stabilizing force in the planet's climate engine. Nevertheless, important changes occur during Earth's ice ages, when large volumes of water transfer from the ocean to solid ice accumulation on the land.

The connections between Pleistocene ice sheets and the oceans are still very poorly understood. An important link is inferred from relatively brief (100- and 500-a) intervals in which thick marine layers of ice-rafted material were widely distributed across the North Atlantic. Called "Heinrich Events," these layers are thought to record episodes of massive iceberg discharge from unstable ice sheets (Bond and Lotti, 1995). The youngest Heinrich events date to 17,000 (H1), 24,000 (H2), and 31,000 (H3) a ago. Closely related is the Younger Dryas (YD) event, a global cooling at 12,800 a ago, which is also associated with North Atlantic ice-rafted rock fragments. There is evidence from corals at Barbados that sea level rose spectacularly, ~20 m during H1 and ~15 m just after YD. Such rises would require short-term freshwater fluxes to the oceans, respectively, of ~14,000 and 9000 km^3/a (Fairbanks, 1989). These events are thought to relate to ice-sheet collapse, reorganization of ocean-atmosphere circulation, and release of subglacial and proglacial meltwater, most likely during episodes of cataclysmic megaflooding.

Mars' "Oceans"

Evidence for persistent standing bodies of water on Mars is abundant (Chapman, 1994; Scott et al., 1995; Cabrol and Grin, 1999, 2001). Despite the lack of direct geomorphological evidence that the majority of Mars' surface was ever covered by standing water, the term "ocean" has been applied to temporary ancient inundations of the northern plains, which did not persist through the whole history of the planet. Although initially inferred from sedimentary landforms on the northern plains (e.g., Lucchitta et al., 1986), inundation of the northern plains has been most controversially tied to identifications of "shorelines" made by Parker et al. (1989, 1993). Failure to confirm some of the shoreline landforms on the newer Mars Orbiter Camera (MOC) imagery led some to reject the ocean hypothesis (Malin and Edgett, 1999, 2001), though it is only various shoreline interpretations that can be rejected in this manner, not the hypothesis of plains inundation. Nevertheless, the MGS data confirm the initial observations of a regionally mantling layer of sediment, now called the Vastitas Borealis Formation, covering perhaps 3×10^7 km^2 of the northern plains (Head et al., 2002). This sediment is contemporaneous with the post-Noachian outflow channels, and it was likely emplaced as the sediment-laden outflow channel discharges became hyperpycnal flows upon entering ponded water on the plains (Ivanov and Head, 2001). In another scenario, Clifford and Parker (2001) envision a Noachian "ocean," contemporaneous with the highlands valley networks and fed by a great fluvial system extending from the south polar cap, through Argyre and the Chryse Trough, to the northern plains.

The MEGAOUTFLO model ascribes the episodic formation of Oceanus Borealis on the northern plains of Mars as merely one component of a cycle. Phenomenally long epochs of post-heavy-bombardment time during which the Mars surface had extremely cold and dry conditions are punctuated by short-duration (~10^4 –10^5 a) episodes of quasistable conditions, considerably wetter and somewhat warmer than those prevailing today at the planet's surface. The transition from the long-persistent cold-dry state was induced by cataclysmic outbursts of huge flood flows from the Martian outflow channels.

Megaflood-Ocean Interactions

Terrestrial megafloods influence the global climate system through their interactions with the ocean. A megaflood can enter the ocean either (1) as a buoyant spreading freshwater plume over higher density (salty) seawater (Kourafalou et al., 1996), or (2) as a descending flow of sediment-laden, high-density fluid, known as a hyperpycnal flow (Mulder et al., 2003). The turbidity current deposits of hyperpycnal flows may extend across hundreds, even thousands of kilometers of abyssal plain seafloor, as in the case of the Missoula Floods of the Cordilleran Ice Sheet (Normark and Reid, 2003). Nevertheless, these flows gradually lose momentum as they drop their sediment loads, thereby releasing low-density freshwater from the bottom of deep ocean basins. The buoyant freshwater will then move upward in massive convective plumes (Hesse et al., 2004). These will disrupt the thermal structure of the ocean, with consequences for the currents that distribute heat and moderate climates.

Sediment-charged Martian floods from outflow channels (Baker, 1982) would have entered the ponded water body on the northern plains as powerful turbidity currents. This is the reason for the lack of obvious deltalike depositional areas at the mouths of the outflow channels. High-velocity floods, combined with the effect of the reduced Martian gravity (lowering the settling velocities for entrained sediment) promotes unusually coarse-grained washload (Komar, 1980), permitting the turbidity currents to sweep over the entire northern plains. The latter are mantled by a vast deposit, the Vastitas Borealis Formation, which covers almost 3×10^7 km^2, or approximately one-sixth of the planet's area. This sediment is contemporaneous with the post-Noachian outflow channels, and it was likely emplaced as the sediment-laden outflow channel discharges became hyperpycnal flows upon entering ponded water on the plains (Ivanov and Head 2001). In another scenario, Clifford and Parker (2001) envision a Noachian "ocean," contemporaneous with the highlands valley networks, and fed by a great fluvial system extending from the south polar cap, through Argyre and the Chryse Trough, to the northern plains.

GLOBAL PALEOENVIRONMENTAL CHANGE

Today Mars is too cold and dry to have an Earth-like climate as a stable condition. Its stable state is not to have liquid water on its surface. Earth may also have experienced Mars-like climate phases in its remote past, but these were not stable climatic states. The stable condition for Earth is to have its ocean and atmosphere in continual contact, thereby moderating the climate. Even during its stable periods, such as the current glacial/interglacial cycling, Earth has been subject to short-term climatic changes of considerable magnitude. As noted above, massive floods of freshwater into the oceans are definitely a factor in cataclysmic climate change for the Quaternary Earth. However, this influence also interacts with many other processes that are only partially understood. Among these are (1) releases of methane from gas hydrates, stored in the sediments of the upper continental slopes of the seafloor (Kennett et al., 2000); and (2) changes in atmospheric carbon dioxide (Pierrehumbert, 2004); changes in ice-sheet dimensions (Stuut et al., 2004); and changes in biological productivity (Dugdale et al., 2004). It is clear that feedback processes are involved in the mutual interactions of these and other components of the global climate system. Could such feedback processes ever have driven Earth to ultraextreme climates?

"Icehouse" and "Greenhouse" Earth

In the 1960s atmospheric scientists began employing relatively simple energy-balance climate models to investigate feedback mechanisms for Earth's climate system. One important problem they encountered was the "faint young sun paradox," wherein solar irradiance is known to be increasing through time as a consequence of the thermonuclear evolution of the Sun. If the early Earth received much less irradiance, perhaps ~30% less during its first billion years (Gough, 1981), its surface should have become totally frozen. The initial growth of ice sheets induced by lower solar irradiance will be subsequently enhanced by the ice-albedo effect on climate change (Budyko, 1966). This positive feedback creates a fundamental instability (Erikson, 1968; Budyko, 1969; Sellers, 1969) such that a "runaway" cooling occurs after about half Earth's surface becomes ice covered.

The 1960s climate modelers knew geological evidence indicated that, at least generally for the last 3.9 Ga, Earth has had liquid oceans and related aqueous processes on its surface. The paradox is further enhanced by the presumption that Earth's frozen state would be irreversible. The ice-covered Earth would have such a high albedo that even the progressive increase in solar irradiance would never be able to bring mean surface temperatures above freezing. In essence this frozen Earth would have a climate very similar to that of present-day Mars. Without the moderating influence of ocean-atmosphere interactions, annual temperatures everywhere would remain below freezing. As on Mars, however, there would be huge diurnal and seasonal temperature oscillations, so that local summer temperatures would reach afternoon highs above freezing. The cycling of water would be extremely limited, dominated by sublimation instead of evaporation, even though immense reservoirs of water would be present beneath the frozen surfaces of the oceans.

The resolution to the "faint young sun paradox" is generally believed to be the greenhouse effect of carbon dioxide. Over long geological time scales Earth's "greenhouse" is presumably stabilized by the interaction of plate tectonics with the global carbon cycle (Walker et al., 1981). Carbon dioxide released through volcanoes continually adds to the atmosphere, but it is removed by precipitation over the continents. The dissolved carbon dioxide produces a slightly acidic precipitation, which reacts with silicate minerals, thereby generating mobile metal cations, silica, and bicarbonate. These eventually get precipitated, commonly in the shells and tests of marine organisms. Subduction of the seafloor, enriched in silica and carbonates, generates metamorphic reactions in Earth's mantle, liberating carbon dioxide, which rises with the magmas that subsequently degas at volcanoes, thereby completing the cycle. This long-term carbon cycle seems to operate with sufficient efficiency for Earth to remain in a "greenhouse" state, avoiding the "icehouse" state predicted by the "faint young sun paradox."

"Snowball Earth" Events

Although Earth never entered a permanent "icehouse" state, it did experience major epochs of glaciation, such as the global cooling initiated in the Oligocene. Extending from 35 Ma to the present period of Quaternary glaciations, this period is only the most recent of several prolonged, extensive glaciations ("megaglaciations"), each lasting several tens of Ma and separated by hundreds of Ma. Meglaciations also occurred during the Permian/Carboniferous, 320–260 Ma; the Neoproterozoic, 750–570 Ma; the Paleoproterozoic, 2400–2200 Ma; and possibly the Archean, 2990–2910 Ma (Crowell, 1999).

The Neoproterozoic megaglaciations are divided into an older phase, the Sturtian, and a younger phase, the Marinoan. The deposits associated with these glaciations are remarkable for (1) their widespread, low-latitude distribution (Harland, 1964; Evans, 2000); (2) the presence of banded iron formations (BIFs) which otherwise are common in the Earth record only prior to ~1.85 GA (Klein and Beukes, 1993), probably because of the evolution of oxygen in the atmosphere (Holland, 1994); and (3) very unusual cap carbonate deposits that commonly overlie the glacial deposits with knife-sharp contacts (Hoffman et al., 1998). Associated varved deposits and fossil ice wedges are interpreted to result from very strong seasonal temperature variations over long time periods (Williams, 1993). Williams (1975, 1993, 2005) explains these features as the result of extremely high obliquity (>54°) during Earth's early history.

Kirschvink (1992) introduced a hypothesis for the Neoproterozoic glaciations that he named the "Snowball Earth Hypothesis" (SBEH). During the Neoproterozoic, continental land masses were concentrated at middle to low latitudes. Because land is more reflective of solar energy than is ocean water, the energy-absorbing character of Earth's tropics was reduced. If temperatures could be lowered in such a situation by additional effects on the "greenhouse," runaway cooling might be initiated by the ice-albedo effect. One possible mechanism for this is the heavy precipitation over relatively small, low-latitude continents, resulting in carbon dioxide removal from the atmosphere because of intense silicate weathering (Hoffman and Schrag, 2002). As the Earth entered its "icehouse" phase, a global freezing over would isolate the oceans from the oxygenating effect of the atmosphere. The resulting anoxic conditions then lead to the concentration in seawater of ferrous iron from submarine hydrothermal sources (Kirschvink, 1992). However, as carbon dioxide was introduced by continuing volcanic emissions, atmospheric concentrations would build up, without the removal process of silicate weathering on the ice-covered continents. This eventually results, after several Ma, in a "super-greenhouse" that melts the global ice cover, reoxygenating the oceans so that they rapidly deposit their iron as the otherwise enigmatic BIFs (Kirschvink, 1992). Hoffman et al. (1998) added the explanation of the cap carbonates as the result of the newly exposed continental land surfaces experiencing especially intense weathering in the "supergreenhouse." The resulting immense flux of alkalinity (metal cations and bicarbonate) to the oceans would cover the cold-climate glacial deposits with the warm-climate carbonates.

The SBEH is criticized for its oversimplification of complex details of glaciological history and its presumed synchroneity of world-wide glaciations (Young, 2005). However, recent support for the cataclysmic terminations of the Marionoan and Sturtian glaciations is provided by the observation of sharp spikes of iridium in cap carbonates from the Eastern Congo craton (Bodiselitsch et al., 2005). The iridium is presumably introduced from extraterrestrial inputs to the global ice cover over several Ma. Rapid melting of the ice in the glacial-terminating "super-greenhouse" would then introduce the observed iridium spikes into the cap carbonates.

Schrag et al. (2002) propose that "snowball Earth" glaciations could have been initiated because the concentration of continental landmasses in the tropics would have been efficient sites for the burial of organic carbon. The associated oceanic anoxic conditions, generated by oceanic upwelling near these continents, would lead to methane production, concentrating the methane in gas hydrate reservoirs. The slow release of this methane would lead to the observed low values δC^{13} immediately prior to the glaciations. The enhanced greenhouse conditions from the methane would accelerate CO_2 removal from the atmosphere via silicate weathering on the tropical continents. Thus a methane greenhouse would gradually replace the carbon dioxide greenhouse. However, this situation is highly unstable because methane is rapidly destroyed by oxidation in Earth's atmosphere. When the gas hydrate reservoirs were exhausted, new methane could not be added to the atmosphere to replace what was lost, leading to the rapid collapse of the "greenhouse" and a runaway ice-albedo feedback that would take the planet to "icehouse" conditions, i.e., to a snowball glaciation.

There is considerable evidence suggesting that "snowball Earth" glaciations may have provided critical stimuli in regard to the evolution of life. The Neoproterozoic glaciations were followed by the Ediacara, the first large and diverse assemblage of animal fossils. The Paleoproterozoic event immediately precedes a phase of oxidative precipitation of iron and manganese that can be interpreted as a result of evolutionary branching in a superoxide enzyme in archaea and bacteria (Kirschvink et al., 2000).

"MEGAOUTFLO" EPISODES

The immense floods that initially fed Mars' hypothetical Oceanus Borealis could have been the triggers for hydroclimatic change through the release of radiatively active gases, including CO_2 and water vapor (Gulick et al., 1997). During the short-duration thermal episodes of cataclysmic outflow, a temporary cool-wet climate would prevail. Water that evaporated off Oceanus Borealis would transfer to uplands, including the Tharsis volcanoes and portions of the southern highlands, where precipitation as snow promoted the growth of glaciers, and rain contributed to valley development and lakes. However, this cool-wet climate was inherently unstable. Water from the evaporating surface-water bodies was lost to storage (1) in the highland glaciers and (2) as infiltration into the porous lithologies of the Martian surface. This latter effect, more than any lack of precipitation, is the likely cause of the limited upland dissection on Mars (Baker and Partridge, 1986). However, recent high-resolution data show that previous notions of limited upland dissection (e.g., Carr, 1996) were mislead by the available lower resolution imagery.

Progressive loss of carbon dioxide from the quasistable atmospheres of MEGAOUTFLO episodes was probably facilitated by

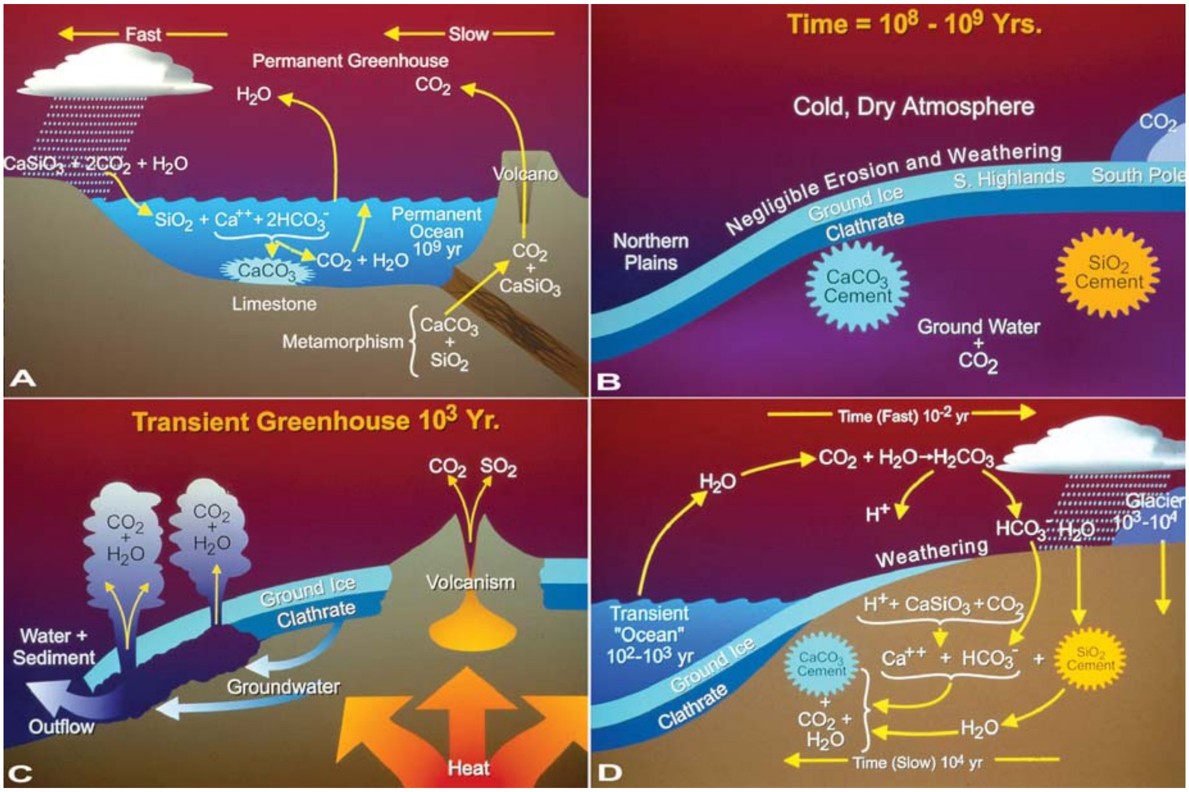

Figure 1. Schematics illustrating long-term cycling of water and carbon dioxide on Earth and Mars. (A) Earth's long-term CO_2 cycle. (B) North-south cross section of Mars' upper crust during the long-term quiescent phase of cold-dry surface conditions, where ground, containing carbon dioxide and perhaps methane, is confined beneath a cryosphere (icy permafrost) that is rich in gas hydrates. (C) MEGAOUTFLO event in which the crust (Fig. 1B) is disrupted by a short-term pulse for tectonic and volcanic activity, while huge outflow events deliver water and sediment to the northern plains and radiatively active gases to the atmosphere. (D) The result is a more Earth-like Mars (compare to Fig. 1A) in which a temporary greenhouse warming promotes active hydrological cycling through the atmosphere; however, this greenhouse would be rapidly terminated because of water storage as glaciers, infiltration of surface water into the porous lithologies of the Martian surface, and silicate weathering that would transfer bicarbonates to the subsurface with the infiltrating water; in centuries or millennia Mars would revert to the conditions illustrated in Figure 1B**.**

(1) dissolved gas in infiltrating acidic water and (2) silicate weathering producing bicarbonate that was carried into the subsurface by infiltration. Subsequent underground carbonate precipitation would then release some of the CO_2 back to the groundwater. However, the developing permafrost from a cooling climate would have trapped this gas in the subsurface. The permafrost zone would have developed as the surface greenhouse effect, promoted by a MEGAOUTFLO episode, went into decline because of the progressive loss of its gases to the subsurface by solution in infiltrating waters. As the permafrost extended downward into the stability field for CO_2 clathrate, this gas hydrate would then accumulate above the gas-charged groundwater. Thus the long-term reservoir for carbon on Mars is a sequestering underground in the forms of (1) clathrate (gas hydrate), (2) gas-charged groundwater, and (3) carbonate cements in crustal rocks. Only occasionally, and for relatively short duration, does carbon get transferred to the atmosphere, as greenhouse-promoting carbon dioxide, during the cataclysmic ocean-forming (MEGAOUTFLO) episodes. Oceanus Borealis (and the later smaller scale lacustrine episodes) does not last long enough in any individual episode for appreciable carbonate deposition. Moreover, the volcanism and water vapor associated with MEGAOUTFLO generate an acidic atmosphere (water, sulfur dioxide, carbon dioxide) that promotes the formation of salt crusts over the entire surface. These ideas seem to explain the lack of observed carbonates in spectra from the Thermal Emission Spectrometer (TES) instrument on Mars Global Surveyor. The short duration of the ocean-forming phases is also consistent with the very low degradation rates (Golombek and Bridges, 2000) for the Martian surface during the long period after heavy bombardment.

The recent discovery of small amounts of methane in the Martian atmosphere (Krasnopolsky et al., 2004) opens up an even more intriguing scenario for MEGAOUTFLO. The methane could be derived from a deep biosphere of methanogens in the Martian groundwater. Isolated below the ice-rich permafrost, this biosphere would produce the more effective greenhouse gas

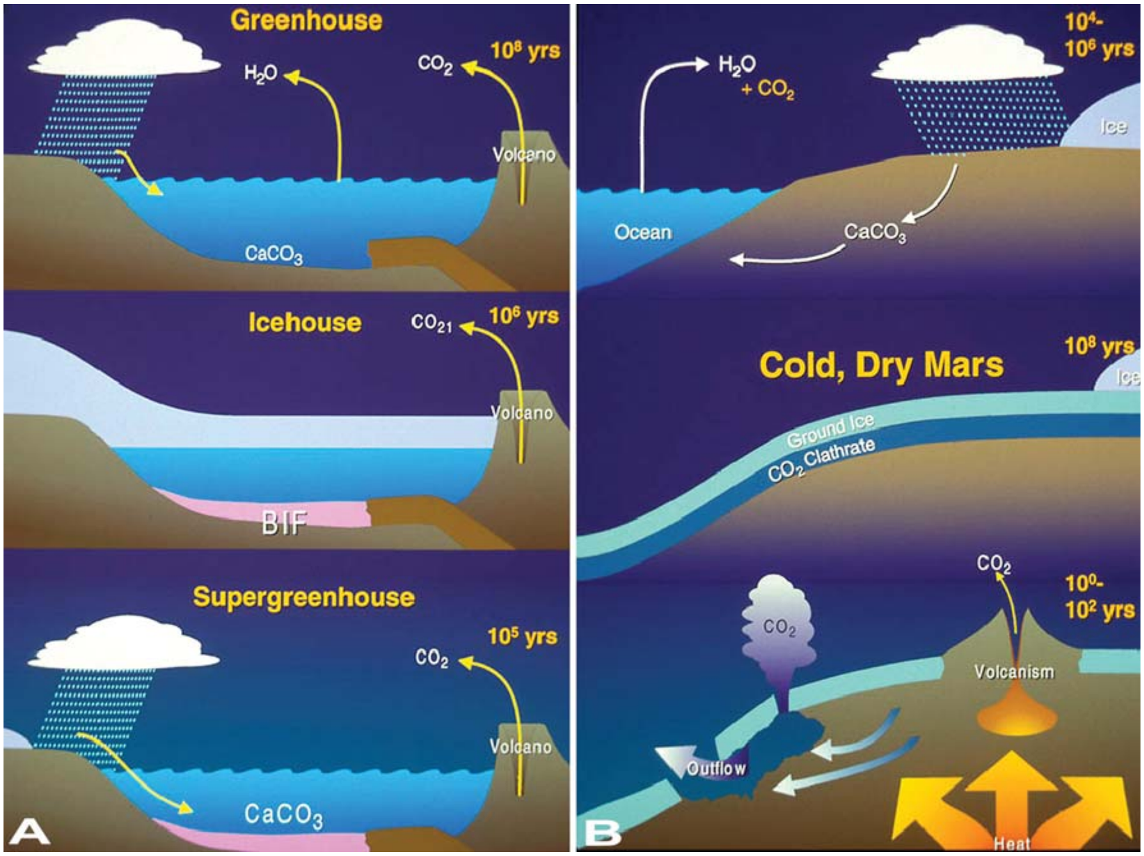

Figure 2. Schematic diagrams comparing the Snowball Earth Hypothesis (A) with the Mars MEGAOUTFLO hypothesis (B; MEGAOUTFLO diagrams correspond, respectively, from top to bottom to Figures 1D, 1B, and 1C). (A) Earth's stable state (upper left) has a persistent ocean in which carbon is precipitated from bicarbonate that is mobilized by the weathering of its landmasses (see also Fig. 1A); if perturbed to a runaway ice-albedo feedback, the ocean can be largely isolated from the atmosphere (middle left), achieving a so-called "snowball" state. The ocean will locally become anoxic, permitting the mobilization of iron and its eventual sequestering as banded iron formations (BIF); however, the continuing outgassing of carbon dioxide to the atmosphere will eventually create a supergreenhouse, melting the ice and producing the very intense weathering that brings cap carbonates to the oceans (lower left). Each of these phases has an equivalent in the MEGAOUTFLO scenario (right on "B").

methane, which would be stored in the ground ice as gas hydrate. Release of methane by MEGAOUTFLO episodes (one of which seems to have occurred in very recent geological time) would then have produced even more effective quasistable atmospheric warming than would be possible with carbon dioxide.

DISCUSSION

In a very broad sense, the Mars cataclysmic outflow events and associated cycles of MEGAOUTFLO can be considered to be broadly analogous to the terrestrial episodes of supercontinent assembly and breakup that are associated with megaglaciations. Continental positioning impacted Earth's long-term carbon cycling, perhaps triggering the spectacular "snowball" glaciations. Icehouse/greenhouse transitions occurred on both planets. Because of the continuous presence of an ocean on its surface, the megafloods of Earth seem to have been only effective at changing climate within an overall glacial epoch. For Mars, the MEGAOUTFLO hypothesis envisions a central role for megaflooding to induce global climate change.

The stable state for Earth throughout its geological history is one of balance between (1) carbon dioxide input to the atmosphere by volcanism and (2) carbon dioxide removal by weathering of continental rocks and precipitation as marine carbonates (Fig. 1A). In contrast, the stable state for long periods of Mars history is carbon dioxide sequestration in groundwater and ground ices (Fig. 1B), including clathrates. During the Proterozoic megaglaciations, however, Earth switched to a cold-dry, Mars-like icehouse. The SBEH proposes that this occurs by freezing over of the global ocean. This extreme state is unstable, and it is terminated cataclysmically when carbon dioxide released from volcanism builds to a critical supergreenhouse level, resulting in melting of all surface ice and the very rapid drawdown of atmospheric CO_2 and associated precipitation of carbonates (Fig. 2).

Similarly, MEGAOUTFLO holds that Mars' stable cold-dry state is terminated by cataclysmic outburst flooding, injecting carbon dioxide (and perhaps other greenhouse gases) into the atmosphere (Fig. 1C). For short periods of time (perhaps thousands of years), Mars experienced an Earth-like water/carbon dioxide cycle (Fig. 1D).

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