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Episodic Ocean-Induced CO_2 Greenhouse on Mars: Implications for Fluvial Valley Formation

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Pulses of CO_2 injected into the martian atmosphere more recently than 4 Ga can place the atmosphere into a stable, higher pressure, warmer greenhouse state. One to two bar pulses of CO_2 added to the atmosphere during the past several billion years are sufficient to raise global mean temperatures above 240 or 250 K for tens to hundreds of millions of years, even when accounting for CO_2 condensation. Over time, the added CO_2 is lost to carbonates, the atmosphere collapses and returns to its buffered state. A substantial amount of water could be transported during the greenhouse periods from the surface of a frozen body of water created by outflow channel discharges to higher elevations, despite global temperatures well below freezing. This water, precipitated as snow, could ultimately form fluvial valleys if deposition sites are associated with localized heat sources, such as magmatic intrusions or volcanoes. Thus, if outflow channel discharges were accompanied by the release of sufficient quantities of CO_2, a limited hydrological cycle could have resulted that would have been capable of producing geomorphic change sufficient for fluvial erosion and valley formation. Glacial or periglacial landforms would also be a consequence of such a mechanism.

I. INTRODUCTION

Baker *et al.* (1991) proposed that a variety of anomalous geomorphological features on Mars can be explained by relatively brief periods of CO_2 greenhouse warming resulting from episodic ocean formation (Parker *et al.* 1989) throughout the planet's geological history. Oceans would have formed as cataclysmic groundwater outflow carved the outflow channels and pooled in the Northern Plains. Baker *et al.* suggested that the release of such enormous discharges was triggered by the extensive Tharsis volcanism and an associated massive hydrothermal system. According to Baker *et al.*, ocean formation may explain the presence of ponded sediments (Jöns 1985, Lucchitta 1986), whorled patterns of multiple ridges and other evidence of paleo lakes (Scott and Chapman 1991), or temporary regional flooding (Lucchitta *et al.* 1985) in the Northern Plains of Mars. Such an ocean or sea may also help to explain various features in the Northern Plains interpreted by Parker *et al.* (1989, 1993) as coastal erosional landforms (e.g., shorelines) and as glacial landforms by Kargel *et al.* (1995).

In the Baker *et al.* (1991) hypothesis, the events surrounding outflow channel formation are assumed to release CO_2 into the atmosphere. The authors discuss several sources of atmospheric CO_2: venting by associated volcanism, release of gasses dissolved in the groundwater, deadsorption of gasses from inundated regolith, and vaporization of clathrate in the regolith and ices resident in the polar caps. Baker *et al.* estimate that up to 4 bar of CO_2 may be released by these mechanisms. Therefore, the ocean causes, and in turn is stabilized by, a thick CO_2 atmosphere.

While detailed consideration of the mechanism(s) for gas release is beyond the scope of this paper, we do suggest some additional possibilities. First, the groundwater released in the formation of the outflow channels may have been especially CO_2 rich. Baker *et al.* (1991) estimated that over 1 bar of CO_2 may have been dissolved into groundwater responsible for the largest possible ocean, but did not consider the various possible origins of CO_2 in groundwater.

There are several ways groundwater can become charged with CO_2. Atmospheric CO_2 can dissolve into surface water which then infiltrates into the subsurface. CO_2 gas trapped in the ground pore spaces can dissolve into percolating groundwater. Naturally occurring inorganic acids such as sulfuric and nitric acids can dissolve carbonates and release free (unbound) CO_2 directly into the groundwater system (Mathess and Harvey 1982).

When associated with volcanism, CO_2 can either have a primary magmatic origin or a secondary origin. In the

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former, CO_2 gas released from underlying magma may dissolve directly into geothermal fluids (Stefansson 1981). This process is particularly efficient under high pressures, as might be achieved in a confined aquifer system. On Mars such conditions may occur in groundwater confined beneath the ice-rich permafrost. In the latter case, it can be released from carbonate rocks by thermal metamorphism or result from dissolution of carbonates by hydrochloric acid in magmatic gasses (Mathess and Harvey 1982). Griffith and Shock (1995) conclude that there may be a substantial reservoir of CO_2 (at least 1 bar) sequestered as carbonate minerals in fossil hydrothermal systems on Mars.

Regardless of the actual origin, if pulses of CO_2 were released into atmosphere of Mars throughout the planet's history, they may have been responsible for the relatively short greenhouse periods that Baker *et al.* suggest to be evident in the geologic record. In particular, such transient greenhouse periods would help to account for fluvial, glacial, and periglacial events late in the planet's history such as the high density fluvial valley networks on the northern flank of Alba Patera (Gulick and Baker 1989, 1990), the suite of putative glacial landforms in the southern hemisphere (Kargel and Strom 1992), possible lacustrine features (Squyres 1989, Nedel *et al.* 1987), and the late formation of periglacial debris mantles (Carr 1977, Squyres 1978; Squyres 1989).

A key question in the Baker *et al.* model is the climatic stability of an enhanced CO_2 greenhouse on Mars late in its history. A thick CO_2 greenhouse has previously been considered as a possible explanation for the ancient valley networks that formed early in Mars geological history (Pollack *et al.* 1987 and references therein). However, such a thick CO_2 atmosphere suffers from two problems which limit its efficiency and even its efficacy in producing early warm climatic conditions on Mars. Several previous studies have pointed out that any dense CO_2 atmosphere on Mars would be transformed into carbonate rocks in the presence of liquid water (e.g., Fanale 1976, Kahn 1985, Pollack *et al.* 1987). The time scale for decreasing atmospheric CO_2 from 1 bar to its present value by carbonate formation has been estimated to be a few 10^7 years (Kahn 1985, Pollack *et al.* 1987). In the absence of recycling, the lifetime of any dense atmosphere would be limited. Furthermore, Kasting (1991) concluded that greenhouse warming by CO_2 alone may not be possible at all early in the planet's history due to the condensation of CO_2 in the atmosphere and ultimately on the surface. For later epochs, the solar luminosity is higher than at the time of formation of the ancient valley networks and CO_2 condensation may pose a lesser problem. These two effects, carbonate formation and CO_2 condensation, set the limits to the CO_2 greenhouse effect on Mars.

In this paper, we investigate the climatic effect of instantaneous pulses of CO_2, such as hypothesized in the Baker *et al.* model, added to the martian atmosphere at 0, 1, 2, and 3 Ga. We utilize a model that explicitly treats carbonate formation and CO_2 condensation (Haberle *et al.* 1994). In the following section, we briefly describe the main features of this model and then present the results for the ocean-induced CO_2 atmospheres. We then discuss the geomorphological implications of these results.

II. MODEL DESCRIPTION

To test the impact of a single pulse of CO_2 injected into Mars' atmosphere relatively late in the planet's history, we utilized the climate model of Haberle *et al.* (1994). This model was originally employed to explore how the evolution of surface temperatures and pressures on Mars from 4.5 Ga to the present depends upon the initial CO_2 abundances. The Haberle *et al.* model is similar to Gierasch and Toon's (1973) energy balance model except that it accounts for a greenhouse effect. Surface and atmospheric temperatures for the polar and equatorial regions are computed for a given surface pressure and solar luminosity. Equilibrium partitioning between the atmosphere, the planetary regolith, and the permanent polar CO_2 caps are computed and treated as exchangeable CO_2 reservoirs. The model draws on published estimates of the main processes thought to affect the atmospheric inventory of CO_2 during this period: chemical weathering (Pollack *et al.* 1987), regolith uptake (Fanale *et al.* 1982), polar cap formation, and atmospheric escape (Luhmann *et al.* 1992). CO_2 losses to space and carbonate formation are irreversible. While there are some mechanisms which could recycle carbonates to the atmosphere (see Section I) they are not considered in the model.

Here we employ the baseline model of Haberle *et al.* (1994) except that both the Kasting (1991) and Pollack *et al.* (1987) greenhouse models are considered. Since weathering rates are controlled by the available quantity of surface water, we considered a variety of cases. Cases with 5, 10, 20, and 27% of the planetary surface area covered by water were explored. Pollack *et al.* (1987) assumed 5% coverage in their model; Baker *et al.* calculated a maximum ocean size covering approximately 27% of the planet's surface, as well as intermediate ocean sizes equivalent to 10 and 20%. According to Baker *et al.*, the largest ocean would have a volume equal to 6.5×10^7 km^3 with an average depth equal to 1.7 km, the intermediate ocean would have a volume equal to 3.1×10^7 km^3 with an average depth equal to 1.1 km, and the smallest ocean would have a volume equal to 1.0×10^7 km^3 with an average depth equal to 0.7 km.

Individual CO_2 pulses of 0.5, 1.0, 2, or 4 bar were injected into Mars' atmosphere at 3, 2, 1, or 0 Ga to determine the effect of these size CO_2 pulses on the planet's global, equatorial, and polar atmospheric temperature and pressure. The baseline model uses the Pollack *et al.* (1987) greenhouse model. Pollack *et al*. (1987) computed the greenhouse effect of a thick CO_2 atmosphere without including the effect of condensation. For a solar luminosity of 0.7 times the present, this model predicts that global average surface temperatures will rise above freezing for about 5 bar of CO_2. For the present solar flux, only 2 bar of CO_2 are needed. In our calculations, we define an effective emmisivity of the atmosphere such that the surface energy balance gives a surface temperature equal to that expected from the Pollack *et al.* results (for a more complete description see Haberle *et al.* 1994). We refer to this model as the Pollack *et al*. greenhouse. The results of Kasting (1991) suggest that there is a limit to the amount of greenhouse warming that a CO_2 atmosphere can sustain due to condensation of CO_2. Therefore, we also use an alternative parameterization that reproduces the surface temperatures determined by this model. We refer to this model as the Kasting greenhouse.

Most models (but see Section IIIC) begin with a nominal 1 bar initial inventory of CO_2 at 4.5 Ga. Haberle *et al.* (1994) concluded that initial CO_2 inventories of 0.5–1.0 bar best satisfy the present day size constraints of CO_2 reservoirs. The details of the subsequent evolution are discussed by Haberle *et al*. Essentially the atmospheric CO_2 reservoir is buffered by the polar caps and remains near 10 mbar. There is some exchange between the permanent cap, the regolith, and the carbonate CO_2 reservoirs with the cap reservoir decreasing and the latter two increasing with time. The global mean temperature increases gradually as the Sun brightens.

At 0, 1, 2, or 3 Ga, an additional 0.5, 1.0, or 2 bar CO_2 pulse is injected into the atmosphere and model integration continues to the present day. These particular pulse sizes were selected to represent those proposed by Baker *et al.* (1991). In some cases the pulse is larger than the initial model inventory. This is not of concern to the model since by the time the pulses are added, most of the initial CO_2 has left the atmospheric reservoir. The behavior of atmospheric temperatures after the pulse addition is not substantially affected by the initial atmospheric abundance (see Section IIIC).

We also considered an extreme upper limit case of 4 bar CO_2 injected into the atmosphere at either 1 or 2 Ga. This pulse size is in keeping with Baker *et al.*'s upper limit of released CO_2, where they assumed that all water released during outflow channel formation was from melting clathrate rather than pure ice. For this particular case, we considered only 10% water coverage of the planet's surface.

The major CO_2 sources considered by Baker *et al.* were groundwater and CO_2 clathrate. In their estimate of pulse sizes they also included a 20 mbar contribution from the northern polar cap. In our models, sufficiently large CO_2 pulses result in the sublimation of the northern polar cap, which then contributes its inventory of CO_2 to the atmosphere. The amount of CO_2 released by the cap depends on its size, which varies by model case. Estimates of the present-day polar cap CO_2 inventory vary. Jakosky *et al.* (1995) concluded that the polar caps could contain over a bar of CO_2. Recently, however, Mellon (1996) calculated that the polar caps cannot hold more than several hundred millibar of CO_2, because CO_2 clathrate has a lower thermal conductivity than water-ice.

III. MODEL RESULTS

A. Baseline Model

Results for the baseline model are shown in Figs. 1 to 5. After the CO_2 pulse injection at 1 Ga (Fig. 1) or 2 Ga (Fig. 2), the atmosphere becomes unbuffered (no permanent caps exist) and the surface temperature rapidly rises. Since the polar cap contributes its CO_2 to the atmosphere once the temperatures first rise, the total atmospheric CO_2 increase is larger than the pulse size. The regolith reservoir grows in size with the increase in pressure, but the temperature forcing on the regolith resulting from the pressure increase limits the response. As a result, there is more CO_2 released to the atmosphere by the caps than the regolith is able to adsorb.

With warmer temperatures and surface water, the weathering rate increases and the atmospheric CO_2 starts to decay. The growth of the carbonate reservoir is rapid after the pulse and is very sensitive to the amount of this pulse. Therefore the greater the pulse, the faster the carbonate reservoir grows and the more rapidly the surface pressure drops.

As the atmospheric CO_2 inventory falls, so does the surface temperature. In all cases, except for pulses injected at 1 Ga with 5% water coverage (Fig. 3), the atmosphere eventually collapses, polar caps form, and the atmosphere returns to the buffered regime by the present epoch. In the one exceptional case, the weathering rate is not fast enough to allow the atmosphere to collapse and form polar caps by 0 Ga.

Therefore, except for the 5% water coverage at 1 Ga case, the CO_2 pulse model meets the observational constraint that polar caps exist on present-day Mars. This constraint is really a statement that the CO_2 pulses must be accompanied by a sufficiently large aerial extent of surface water. Pulses that occur more recently than 2 Ga in Mars' geological history require that a larger fraction of the planet's surface be covered by water so that increasing weathering rates are sufficient to allow polar caps to form by the present.

The duration of elevated temperatures is more sensitive to the size of the oceans than either the amount of CO_2 in the pulse or the time of pulse injection. Depending on

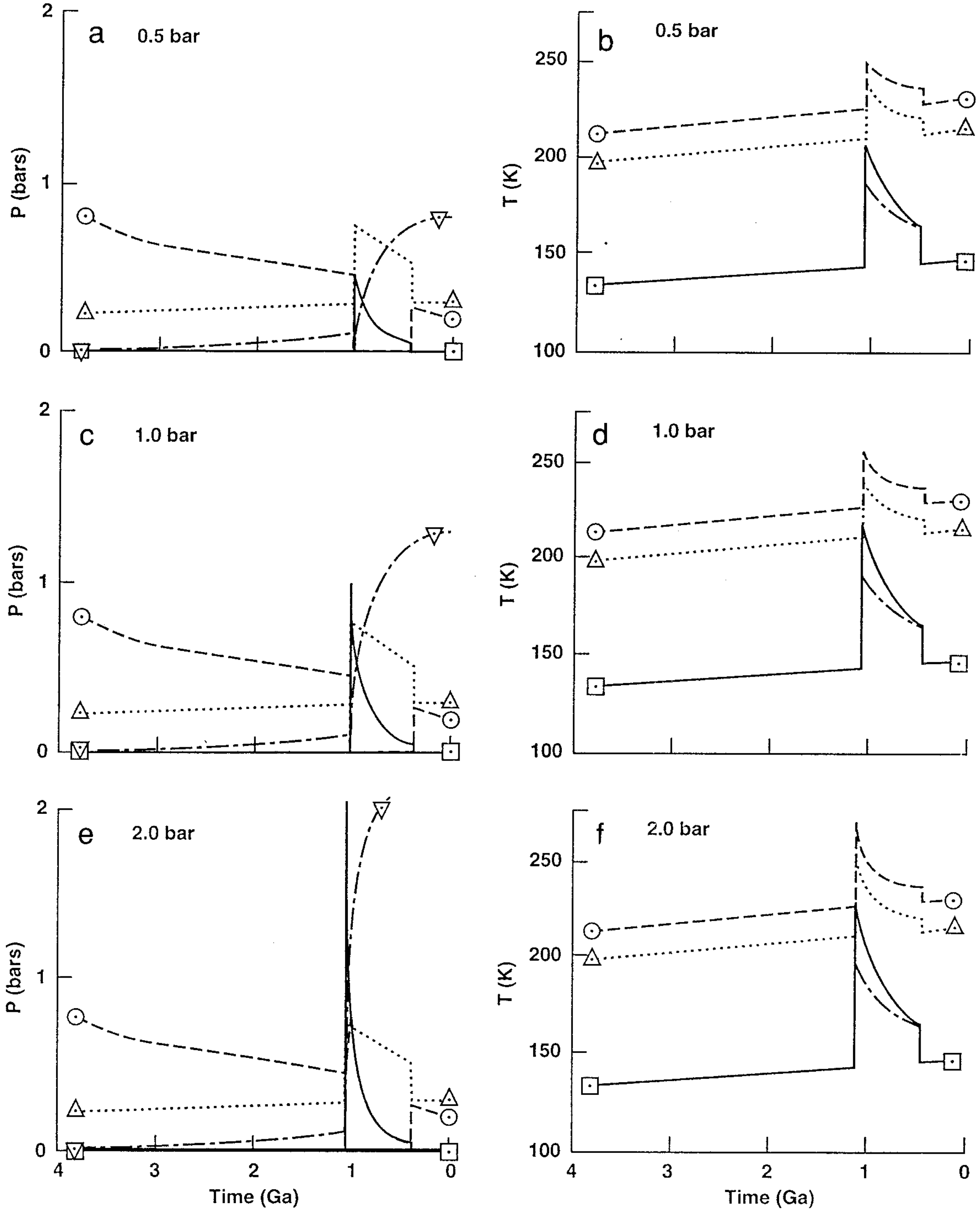

FIG. 1. Temperature and pressure versus time before present in billion years. Plots show the effects of a 0.5, 1.0, and 2.0 bar CO_2 pulse injected at 1 Ga, respectively, assuming 10% water coverage. CO_2 condensation is neglected. In the reservoir (pressure vs time) plots, the solid line with squares is the surface pressure, the dashed line with the circle is the permanent cap reservoir, the dotted line with the upward-pointing triangle is the planetary regolith, and the chain dotted line with the downward-pointing triangle is the carbonate reservoir. Atmospheric escape losses of CO_2 are not shown because the quantity lost to space over the period of interest is minimal. In the temperature vs time plots, the solid line with the square is the polar temperature, the dashed line with the circle is the equatorial temperature, the dotted line with the triangle is the global surface temperature, and the chain dotted line is the frost point temperature. The frost point allows us to see the approach of the climate to atmospheric collapse. When the polar caps exist, the frost point temperature and the polar temperature are equal.

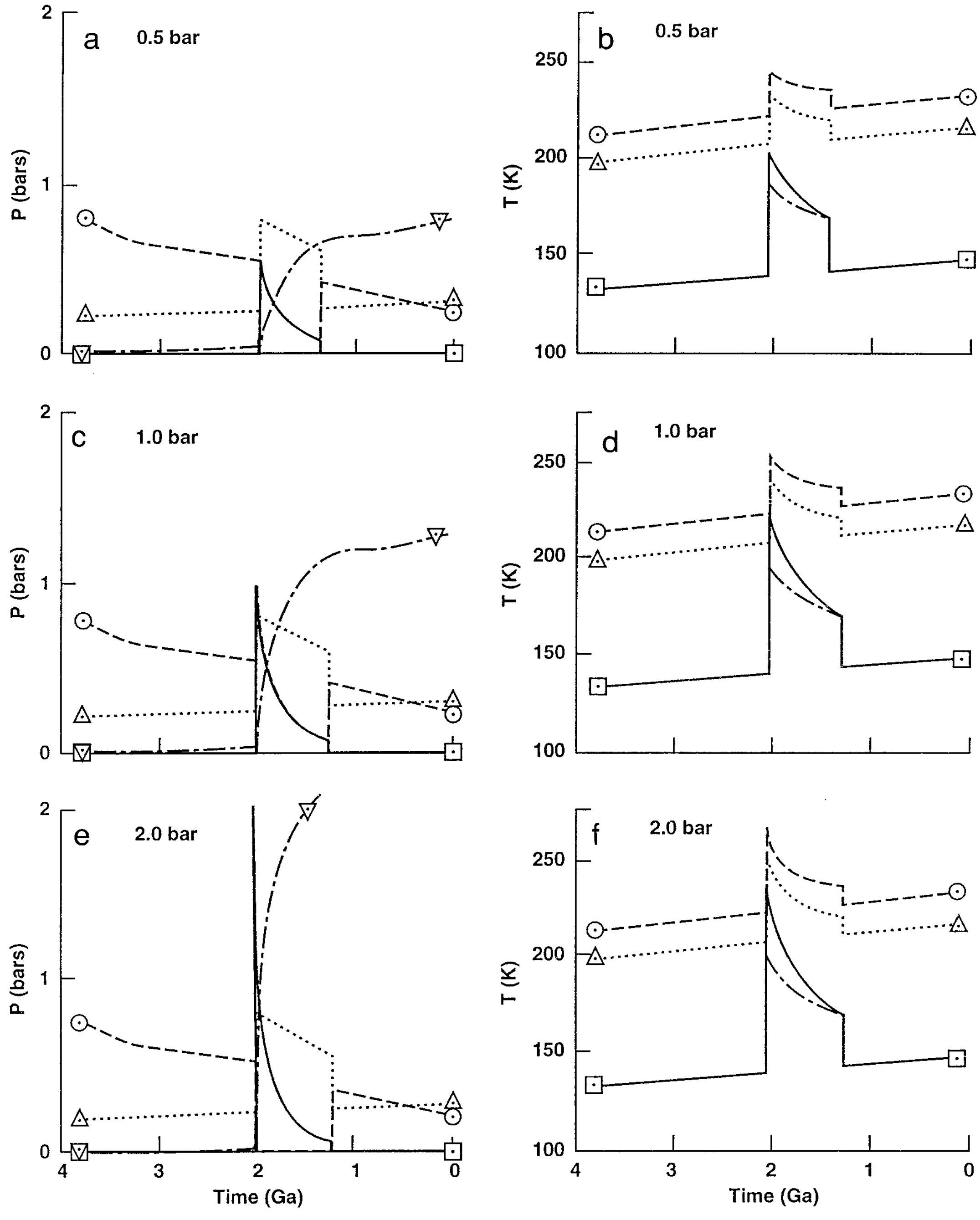

FIG. 2. Temperature and pressure versus time before present in billions of years. Plots are similar to those in Fig. 1 except that pulse injection took place at 2 Ga.

the model, greenhouse warming induced by the CO_2 pulse may last for 3×10^8 to 1×10^9 years. For the 0.5 bar pulse at 1 Ga with 10% water coverage (Fig. 1), equatorial temperatures rise approximately 25 K above the background temperature to approximately 250 K and then slowly decay over a period of 6×10^8 years before the atmosphere collapses. Polar and mean global temperatures rise by 60 and 25 K, respectively, above the pre-pulse temperatures (142 and 210 K) immediately after pulse injection. For a 2.0 bar pulse, equatorial temperatures rise by nearly 50 K and then decay more rapidly over 7×10^8 years to the background temperature (225 K). Polar and mean global temperatures similarly increase by approximately 90 and 50 K above background temperatures (140

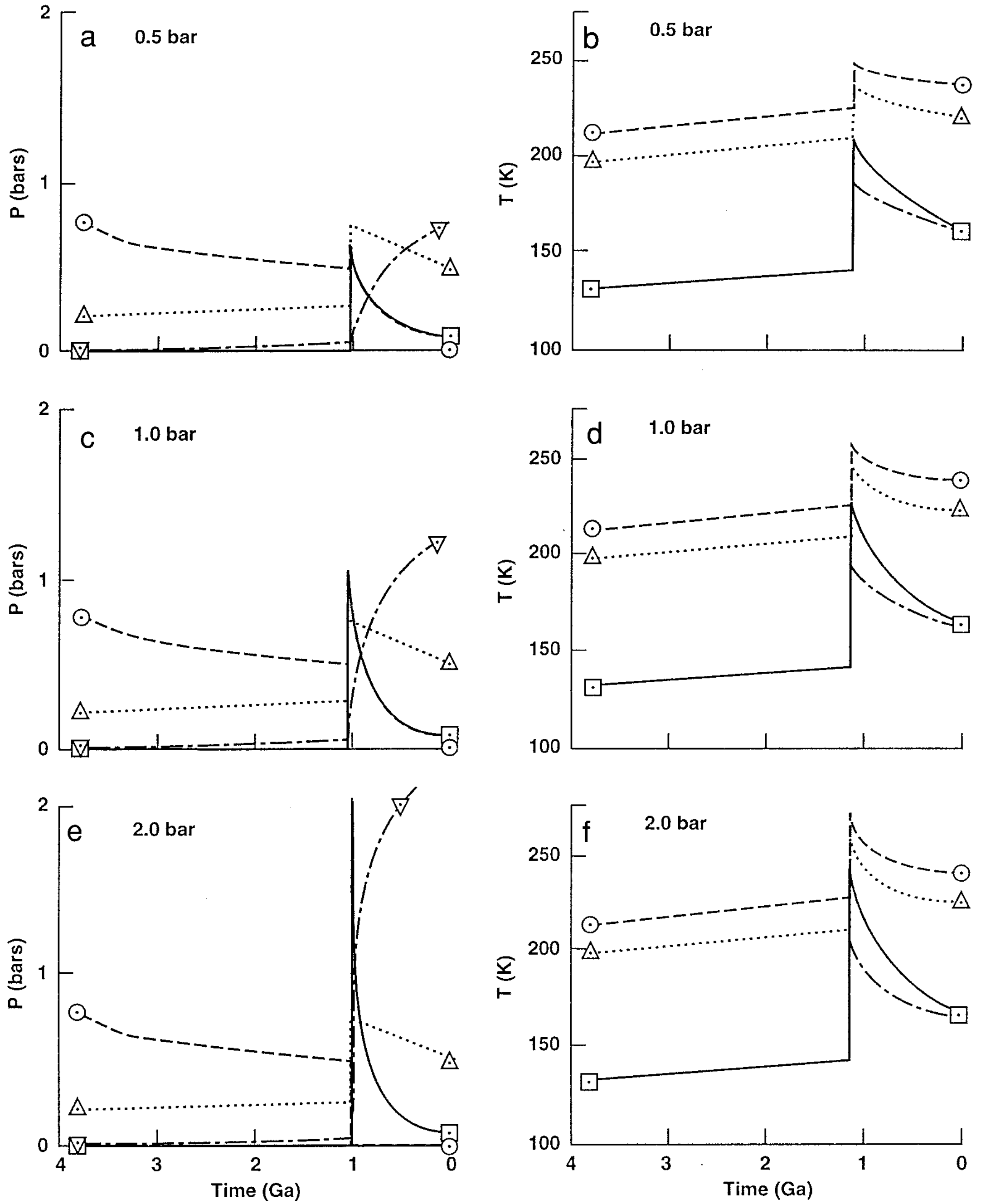

FIG. 3. Plots similar to Fig. 1. Pulse at 1 Ga and ocean 5% water coverage is assumed. Temperature plots indicate that the atmosphere has still not collapsed by 0 Ga.

and 210 K). With 27% water coverage, roughly equivalent to the maximum ocean size reported by Baker *et al.* (1991), the atmosphere collapses in approximately 2×10^8 and 4×10^8 years, for the 0.5 and 2 bar cases, respectively. For the same pulses injected at 2 Ga, results are similar although peak temperatures are about 5 K less owing to the fainter Sun.

Figure 4 summarizes how long atmospheric temperatures remain above 240 and 250 K for various pulse sizes at 1 Ga (a) and 2 Ga (b). Results indicate that for pulse sizes greater than 1 bar at 2 Ga and greater than 0.5 bar at 1 Ga, the atmosphere remains above 240 K for several 10^7 years. In addition, when comparing duration with ocean size, mean global temperatures remain above 240 K ap-

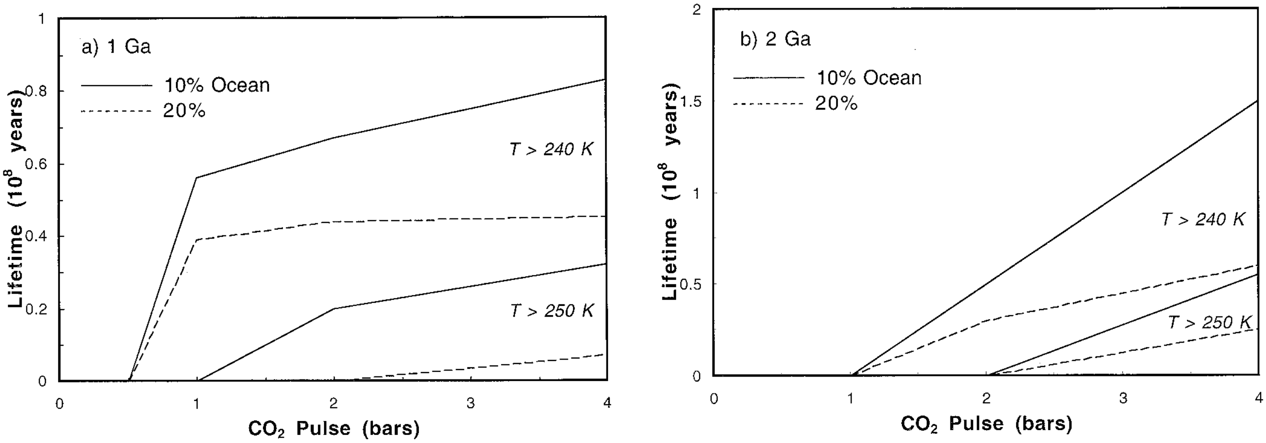

FIG. 4. Lifetime of greenhouse warming for various CO_2 pulse sizes injected at 1 (a) and 2 Ga (b). Lifetimes are shown for mean global temperatures exceeding 240 and 250 K. Global temperatures remain above 240 K roughly twice as long for the 10% water coverage case than for the 20% case. The decline to colder temperatures is slightly faster at 2 than at 1 Ga, due to the lower solar luminosity. Larger oceans produce more rapid weathering of CO_2 into carbonates and thus shorter greenhouse climates.

proximately twice as long when water (or ocean) covers only 10% of the planet's surface than when it covers 20% of the surface.

In general, our modeling indicates that these CO_2 pulses would not be sufficient to raise the equilibrium temperature above freezing, unless we considered a 4 bar pulse (Fig. 5). In this extreme case, global temperatures are elevated above 273 K for several 10^6 years. Unlike early Mars, such conditions are permissible at later times because the Sun is brighter.

B. Effects of CO_2 Condensation

We also evaluated the effects of CO_2 condensation on our results for pulse injections at 1 and 2 Ga by replacing the Pollack greenhouse model with the Kasting greenhouse model. In addition, because there is evidence for valley formation throughout Mars' geological history and because the absolute ages of the dissected surfaces are not known, we also considered the effects of pulses at 0 and 3 Ga.

Results for various pulse sizes at 1 and 2 Ga using the Kasting greenhouse model are shown in Figs. 6 and 7. In general, for the 1 and 2 Ga pulses, we find that the peak temperatures are slightly lower and the time before atmospheric collapse slightly longer than in the baseline model. For the 2 bar case (10% water coverage) at 1 Ga, peak temperatures rise from approximately 227 K before the pulse to 263 K immediately afterward in the equatorial regions, from 142 to 242 K in the polar regions, and from approximately 210 to 255 K globally. The atmosphere collapses in less than 1 Gyr. Note that surface pressures remain at or above 1 bar for approximately 10^7 years after injection of the CO_2 pulse. These temperatures range from 5 to 10 K cooler than the comparable Pollack model and duration of the unbuffered period is approximately 20% longer.

We also considered the effects of CO_2 condensation on pulses injected at 3 Ga (Fig. 8). A 0.5 bar pulse injected at 3 Ga had no measurable effect on global atmospheric temperatures, while 1, 2, and 4 bar pulses raised the global temperatures to 228, 232, and 245 K, respectively. The duration of the unbuffered period was approximately 1.4 Gyrs for the 1 and 2 bar CO_2 pulse and approximately 1.6 Gyrs for the 4 bar case. Surface pressures at or above 1 bar persist for approximately 10^8 years after injection of the CO_2 pulse.

Finally, we considered CO_2 pulse injection at 0 Ga (Fig. 9) to determine the magnitude of global temperature change with CO_2 condensation if such pulses were to occur under present conditions. We find that peak global temperatures would increase to 253, 260, and 286 K for pulses of 1, 2, and 4 bar. Surface pressures at or above 1 bar persist for a few 10^7 years. A summary of the peak global temperatures for various pulse sizes injected at 0, 1, 2, and 3 Ga assuming the Kasting CO_2 condensation is presented in Fig. 10.

C. Effects of Larger Initial CO_2 Inventories

To determine what effect the size of the initial CO_2 inventory might have had on a CO_2 pulse injected at 1 or 2 Ga, we varied the amount of CO_2 in the initial system, while the amount introduced at later times was held constant at 1 bar. In all cases (Fig. 11) weathering reduces the exchangeable inventory to very similar amounts by the time of pulse injection, and the model behavior after CO_2 pulse injection is independent of the initial inventory.

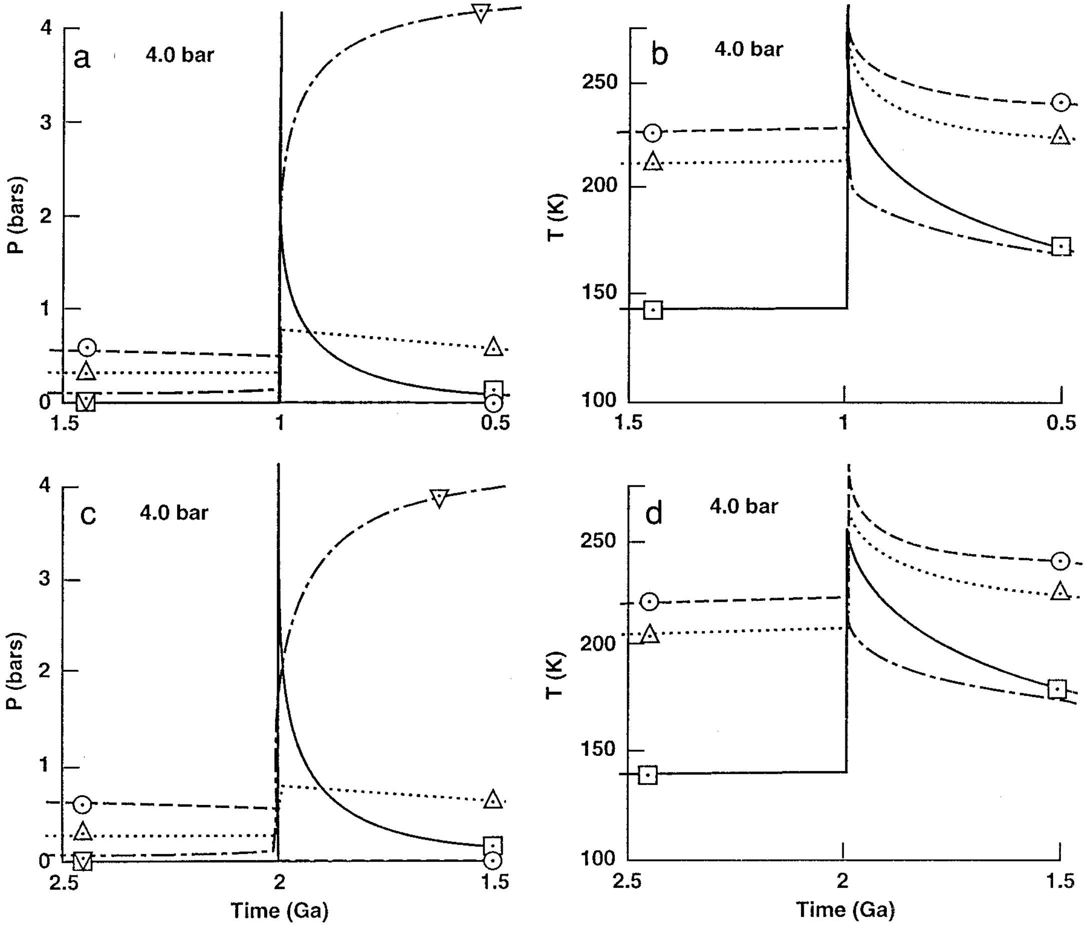

FIG. 5. Results for a 4 bar pulse of CO_2 injected at 1 (a) and 2 Ga (b). Line styles are defined in the legend to Fig. 1.

IV. CLIMATE EVOLUTION AND STABILITY

Baker *et al.* suggested that multiple outflow channel episodes might lead to multiple oceans and CO_2 pulses. In Fig. 12, we illustrate how multiple pulses might cycle the martian climate system through alternating periods of warm and cool conditions. This figure is an adaptation of Fig. 11 in Haberle *et al.* (1994). Point A in the figure represents conditions prior to the first pulse. A permanent polar cap exists and the surface pressure is less than it is today since the Sun is less luminous. When the first ocean-forming event occurs, it vaporizes the cap and releases dissolved CO_2 into the atmosphere. In order for the climate to transition to a warmer state, the total amount released must exceed the difference between the pressure at point B and point A. Less than this and the cap reforms and the system returns to point A. More than this and the system moves up the curve to, say, point C where the climate stabilizes in a warmer temperature regime. The exact location of point C will depend on the amount of CO_2 available to the system. While in this new regime, weathering gradually draws down the atmosphere until reaching point B. With additional weathering the climate collapses (point B is unstable), and the system returns to point A. If the time between ocean-forming events is geologically long, then solar brightening shifts up the solid curve in Fig. 12.

When the next pulse is released (point D), the process is repeated (again, only if the amount released is greater than the difference between point E and point D), but the "warm" regime (point F) is now cooler than the previous one because of the loss of CO_2 to the carbonate reservoir. Thus, multiple ocean-forming events can cycle the martian climate system between warm and cool regimes, but each successive event will have less available CO_2, and hence a cooler climate unless the carbonate reservoir is somehow recycled as well.

V. IMPLICATIONS FOR FLUVIAL VALLEY FORMATION

How would the increase in global mean temperature induced by the pulse affect fluvial valley formation? We

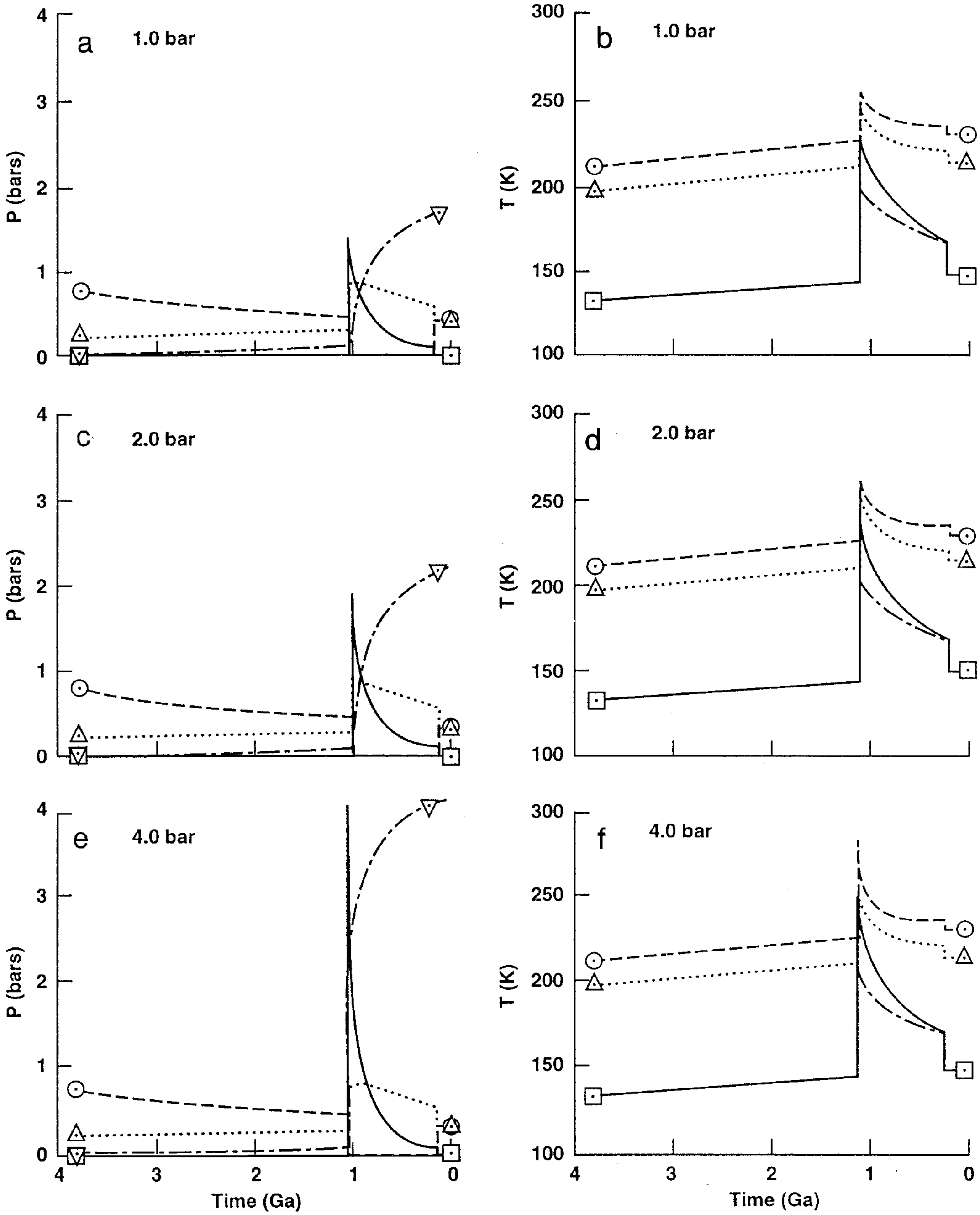

FIG. 6. Pressure and temperature plots versus time before present in billions of years. Plots show results for 1.0, 2.0, and 4.0 bar pulses of CO_2 injected at 1 Ga assuming 10% water coverage. CO_2 condensation (Kasting greenhouse) is included. Line styles are defined in the legend to Fig. 1.

have found that pulses produce a sub-freezing and relatively dense atmosphere. Coupled with the postulated frozen sea or ocean at low elevations resulting from outflow channel discharges, is this combination conducive to valley formation? Clearly for global mean temperatures well above freezing and with a large body of water, a hydrological cycle which includes rain would be expected. Under such conditions, fluvial valleys would form readily and erosion rates would be quite high. However, such a scenario is probably inconsistent with the observed level of preservation of the ancient cratered terrain in the southern highlands of Mars. Attempts to estimate erosion rates have yielded very low numbers (Carr 1992, 1996).

Since our results suggest that, in general, a sudden pulse

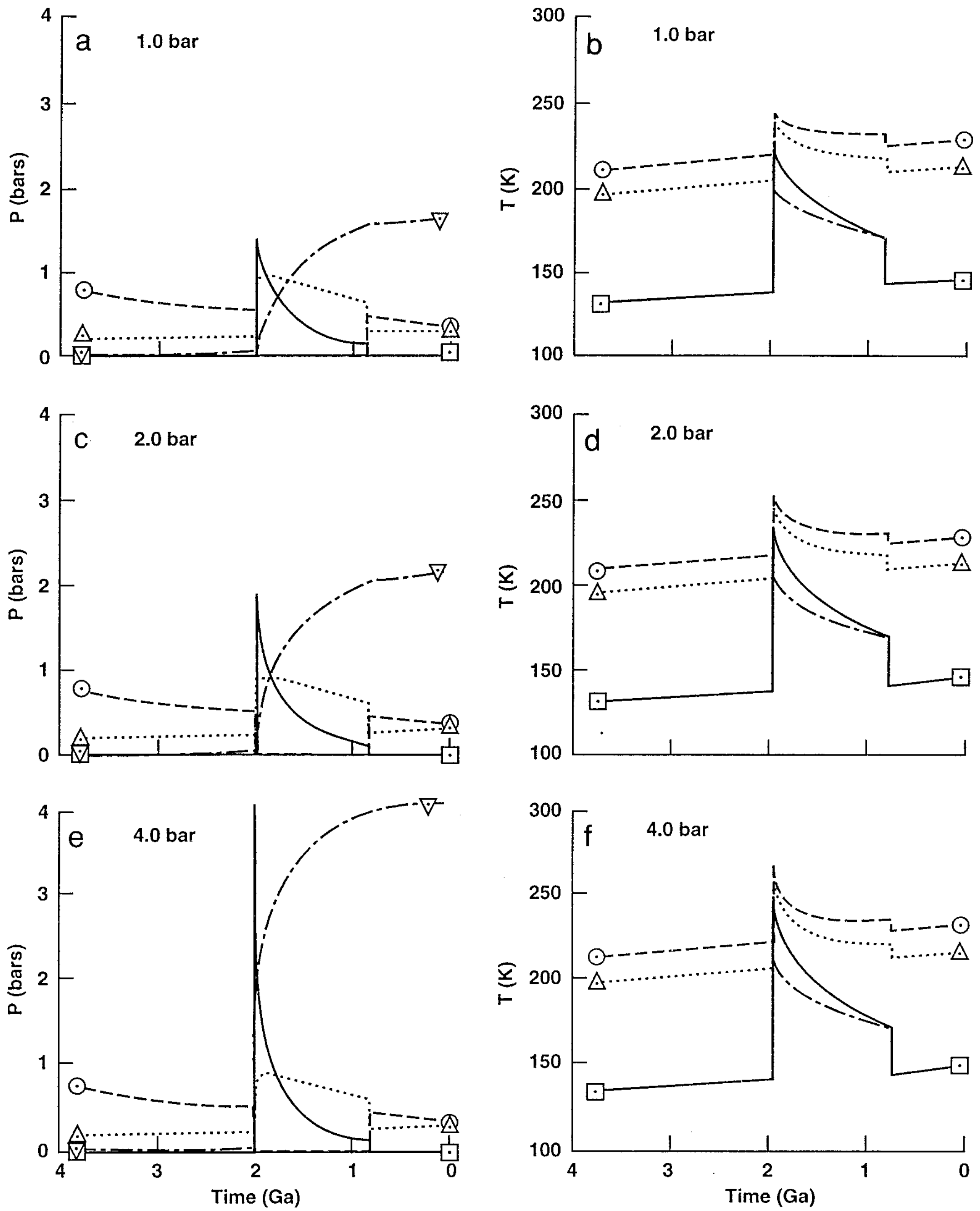

FIG. 7. Same as Fig. 6 for pulse injected at 2 Ga.

of CO_2 injected into Mars' atmosphere does not bring mean global temperatures above 273 K, we must consider if there exists a range of temperatures close to but below freezing at which fluvial valley formation can proceed locally but with a globally low erosion rate. We explore two alternative mechanisms: melting of high-altitude snowpacks by a few warm days a year and by geothermal heating. We assume for both mechanisms that water from frozen seas or oceans is first deposited at higher elevations, either on the flanks of volcanoes or in the Southern Highlands.

Regardless of the melting mechanism, enough water for fluvial erosion must be available. For example, the fluvial valleys on the northern slope of the volcano Alba Patera cover approximately 3×10^4 km^2. The total volume of material removed from this area is about 10^{11} m^3 (Gulick 1993, 1997a). Assuming volume ratios of water to removed

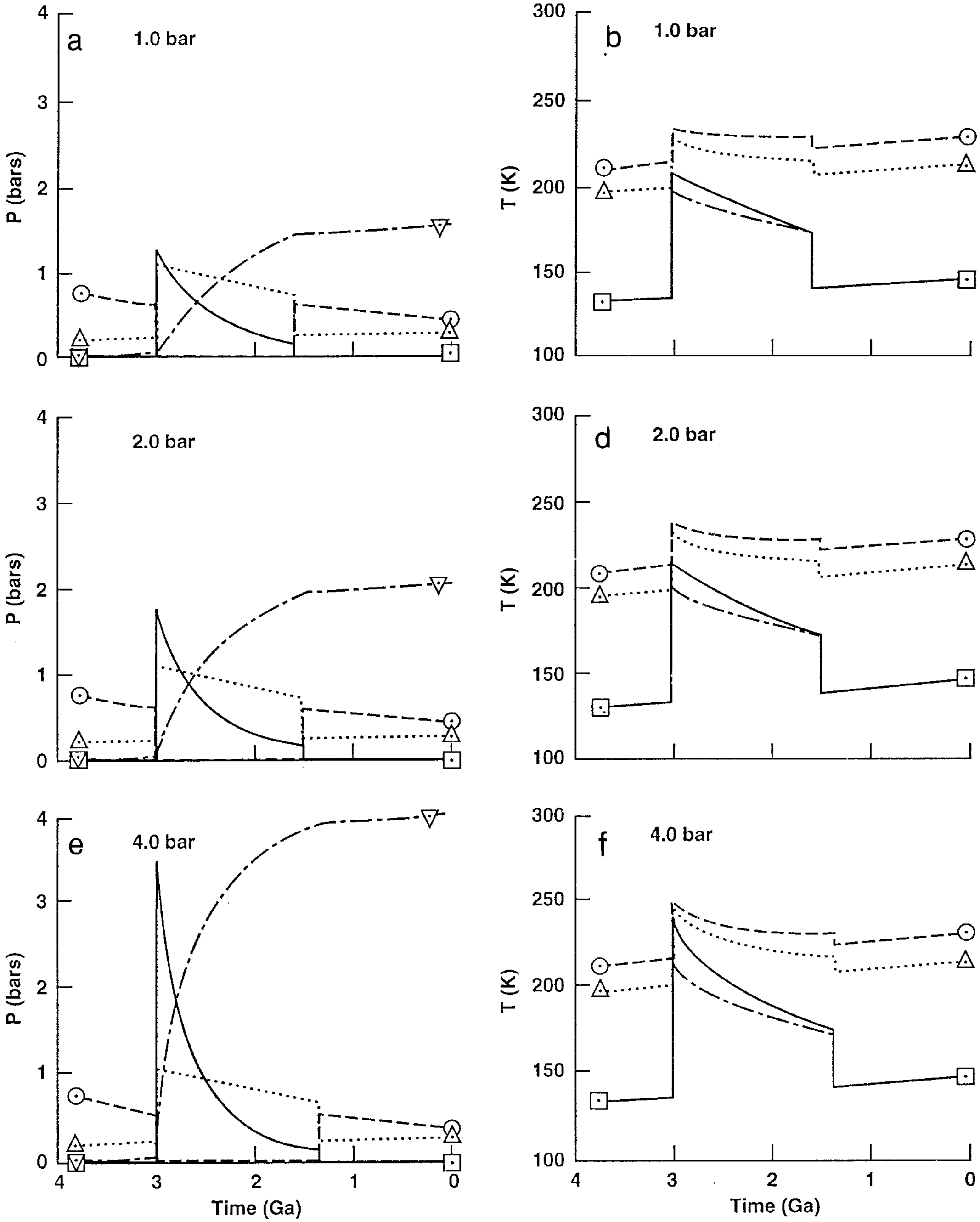

FIG. 8. Same as Fig. 6 for pulse injected at 3 Ga.

material of 1000 : 1, an equivalent depth of water of 10 km over the region would be required for valley formation (Gulick 1993, 1997a). Precipitation, with no atmospheric losses, of 1 cm/year could theoretically provide the necessary quantity of water in 10^6 years (Gulick and McKay 1994).

However it is doubtful that such low precipitation rates could actually induce valley development. For guidance, we turn to the dry, leeward flanks of Hawaiian volcanoes which demonstrate that intensity, as well as duration, is important in valley formation. Regions of West Molokai receive approximately 20 cm/year of rainfall and exhibit very little fluvial erosion. Widely spaced linear streams with little to no tributary development dissect the approximately 2 million year old surface. Some regions on Mauna Loa receive an order of magnitude or more rainfall and

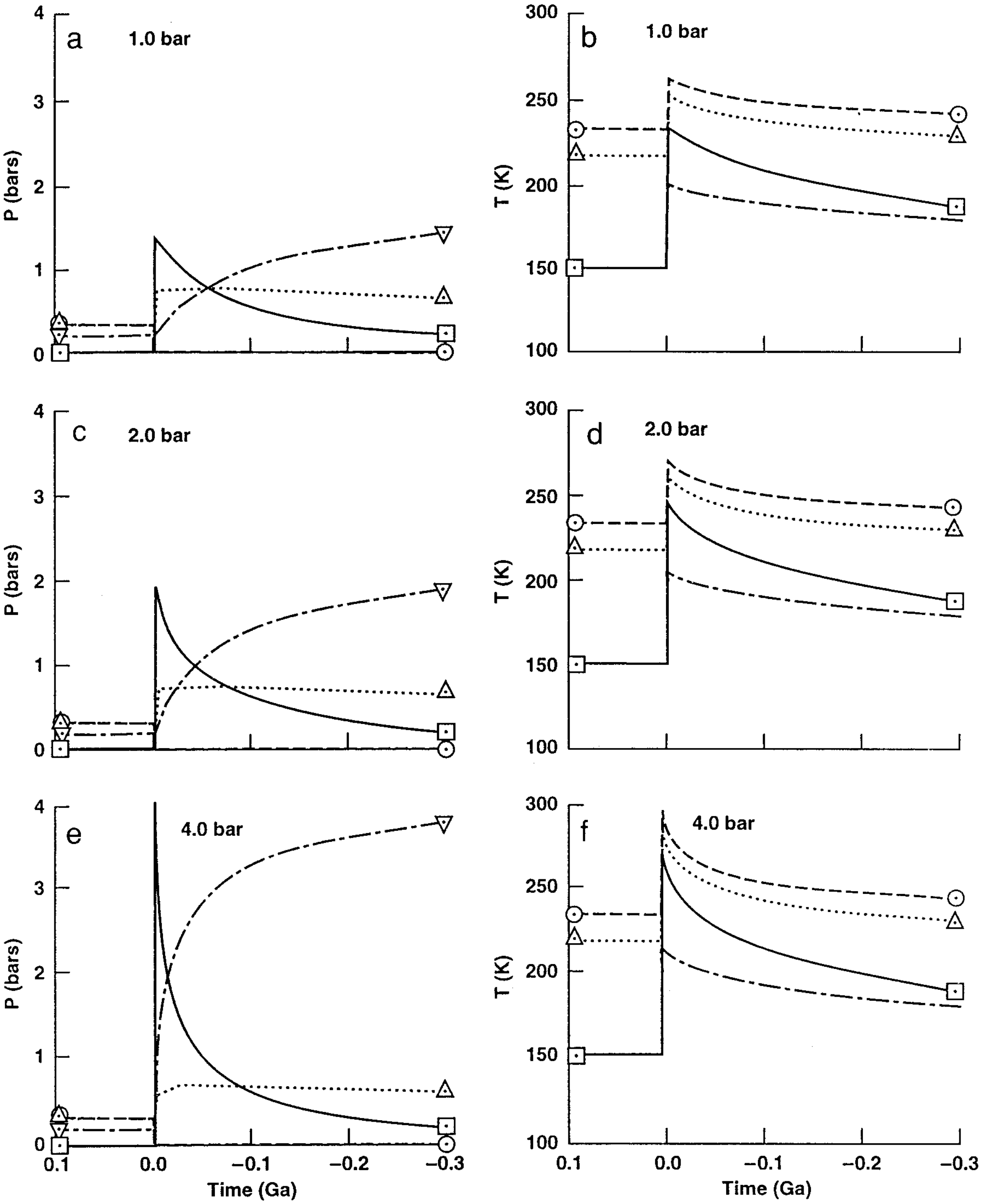

FIG. 9. Same as Fig. 6 for pulse injected at 0 Ga. Notice that both global and equatorial temperatures rise above 250 K for all cases. Lines styles are defined in the legend to Fig. 1.

show comparable or greater degrees of valley development on surfaces 10 times younger. However, the degree of valley development on surfaces older than West Molokai receiving comparable amounts of rainfall is not appreciably greater. Therefore, rainfall rates less than some critical value, estimated to be ~10 cm/year, seem to be insufficient to erode valleys, even over long time periods (Gulick 1997a).

A. Atmospheric Water Transport

We consider transport of water vapor from the surface of the frozen sea to higher elevations. Following the ap-

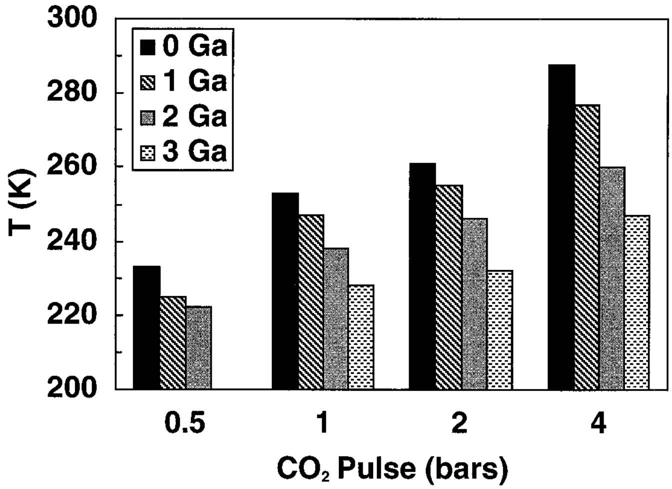

FIG. 10. Maximum temperature produced by atmospheric CO_2 pulses as a function of pulse size and timing for the Kasting greenhouse models. Note that the 0.5 bar pulse at 3 Ga does not produce warming. Equal size pulses produce warmer temperatures at more recent times because of the brighter Sun.

proach of Moore *et al.* (1995), who considered the rate at which water could be delivered to higher elevations from a frozen lake, the model begins with initially dry air that blows over the sea. The air reaches saturation as the underlying ice sublimes (Fig. 13). The rate of sublimation of the ice sheet depends exponentially on the temperature and somewhat on the wind speed. For current martian conditions (~220 K) and wind speeds of 1 to 5 m/sec, sublimation rates are in the range of 0.3 to 3 cm/year. For mean conditions 25 and 50 K warmer than present, the sublimation rates are 10 and 100 times larger, respectively (Fig. 14a).

The saturated air cools as it is lifted upward and part of the entrained water vapor condenses as snow. The fraction of water that is deposited as snow depends on the lapse rate and the height of the ascent—that is the difference between the elevation of the snowfield and the surface of the sea. For current martian mid-latitude temperatures (220 K), the snow accumulation rate over a 2 km altitude change is approximately 1 cm/year of equivalent water, if the snow accumulation area is comparable to the area of the sea. For a 6 km altitude change, appropriate for the summit caldera region of Alba Patera, the accumulation is 40% larger, again assuming no precipitation at intermediate altitudes. While these calculations assume the process is perfectly efficient, if precipitation at intermediate altitudes did occur, the snow would simply accumulate over a larger area. The results depend linearly on the relative areas of the snow field and sea.

The deposited snow, like the sea ice, is subject to sublimation. However, the sublimation rate is lower at higher altitudes due to the lower temperature. The estimated net annual snow production is of order 1 cm/year if the sea were formed under current climatic conditions. Once again the net accumulation would be on the order of 10 and 100 cm/year for temperatures of 240 and 250 K, respectively. As seen in the model results, 1 to 2 bar pulses of CO_2 injected into the atmosphere at 0, 1, 2, and 3 Ga yield global average temperatures remaining at or above 240–250 K for several 10^7 years. Because surface pressures remain at or above 1 bar for periods lasting 10^6 to 10^8 years (depending on the time and, to a lesser extent, the size of initial pulse injection) after injection of the CO_2 pulse, such elevated pressures would keep resulting meltwater in liquid form much longer than under present climatic conditions.

B. Solar Snowmelt

Fluvial activity can result from snowmelt when mean annual temperatures are below freezing if there exists an annually occurring seasonal period when temperatures exceed freezing. This is observed in the Antarctic dry valleys where mean annual temperatures are −20°C but summers experience about 40 thawing degree-days (Clow *et al.* 1988). A degree-day is defined as the integral of temperature over time for temperatures above 0°C. For example, a day where temperatures remain at 10°C over 12 hr equals 5 degree-days and a 2 day period where temperatures remain at 2°C would equal 4 degree-days above freezing. Using a simple parameterization for the seasonal change in climate, McKay and Davis (1991) determined that similar levels of summer warming could occur on equatorial Mars with mean annual temperatures as low as 235 K. This analysis assumes that there exists snowpacks that can provide sources of meltwater when the temperature exceeds freezing.

We can summarize the expected hydrological cycle as follows. For mean annual temperatures above 250 K, there is sublimation from the ice-covered sea or ocean at rates of 100 cm/year or more. This moisture is deposited in the highlands and on the flanks of volcanoes as snow. With continued deposition, permanent snow fields and possibly even glaciers will eventually form. Seasonal warming results in daily average temperatures above freezing and melt water forms from these snow fields and glaciers. In broad outline, this is the hydrological cycle observed in the Antarctic dry valleys.

We conclude that the factor that limits fluvial erosion is the efficiency of the sublimation and deposition cycle. Levels of at least 10 cm/year are required implying mean annual temperatures of 240 K or more. For this mean annual temperature, we expect that seasonal warming would be sufficient to cause liquid water formation from deposited snow and ice.

C. Geothermal Heating

A mechanism that would produce localized melting, and hence erosion, of a wide-spread snowpack is geothermal

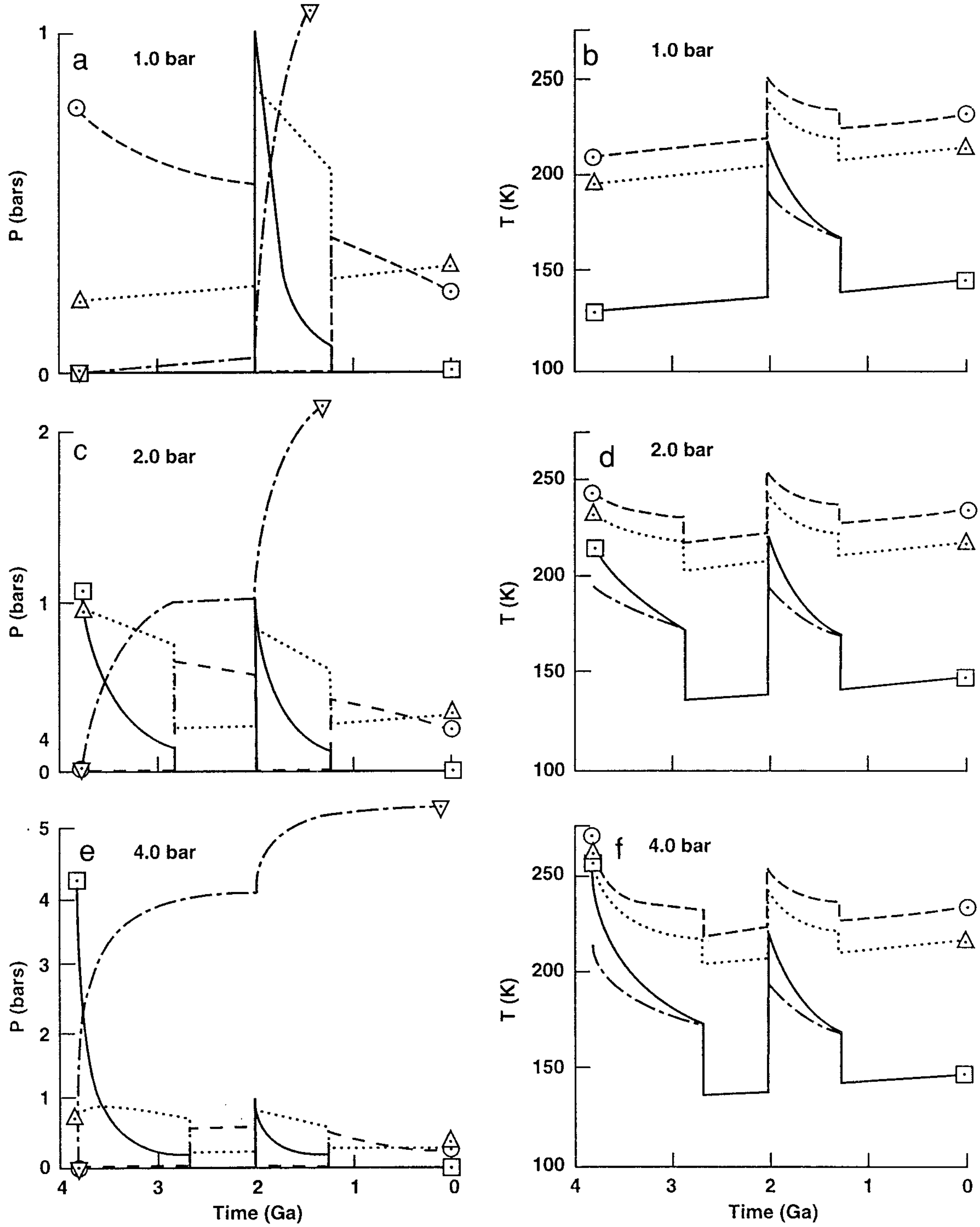

FIG. 11. Pressure and temperature versus time before present in billions of years (Ga). Plots show the effects of a 1.0 bar pulse of CO_2 injected at 2 Ga assuming 10% water coverage. Results for initial CO_2 inventories of 1.0, 2.0, and 4.0 bar (labeled on plots) are shown. Despite variations in the size of the initial CO_2 inventory, response of atmosphere to later pulses is similar. Note change in scale on pressure plots. Line styles are defined in the legend of Fig. 1.

heating. A geothermal heat flux of 0.1 W/m^2 is required to melt a 1 cm annual water equivalent thickness production of snow. Such a heat flow is commonly measured over extensive (10^4 km^2) regions surrounding large terrestrial volcanic centers (e.g., Cascade volcanoes, Washington State, and the Wairakei geothermal system, New Zealand). Heat flows of 1 W/m^2 are commonly measured over areas of 10^3 km^2 in terrestrial hydrothermal regions with the more intense areas delivering on the order of 500 W/m^2 to the surface (Elder 1981). Therefore, the limiting factor

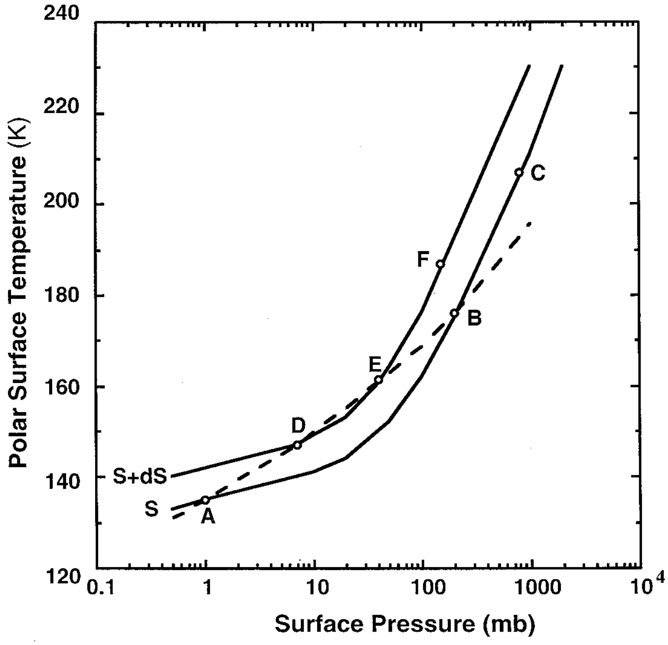

FIG. 12. A schematic illustration of ocean-driven climate cycling on Mars (after Haberle *et al.* 1994). Solid lines labeled S and (S +d S) represent annual mean polar surface temperatures as a function of atmospheric pressure at solar luminosity S. The dashed line is the CO_2 frost point temperature. Possible states are where a solid line crosses the dashed line (unstable when the slope of the temperature curve is greater than that of the frost point curve), or a solid line exceeds the dashed line without polar caps. If the total amount of CO_2 added by a pulse is less than the difference between point B and point A, the carbon dioxide in the atmosphere above the poles will be below the frost point temperature and the atmosphere will collapse, returning the system to point A. If more CO_2 is added to the atmosphere than this difference, the polar caps will be unstable. The climate will stabilize in a warmer, cap-free regime, say at point C. Weathering will then remove available CO_2 until point B is reached and the atmosphere collapses. Polar caps will form with an amount of CO_2 corresponding to the difference between B and A. At some later time (S + dS) with the system at point D, another warming cycle can drive this CO_2 into the atmosphere reaching another stable point F. Loss by weathering will continue until E followed by storage of E minus D in polar caps. Repeated cycles generate ever smaller polar caps.

in liquid water production on the slopes of an active volcano on Mars is snow accumulation, not delivery of sufficient heat from a local thermal source to melt the snow.

While either the solar or geothermal snowmelt hypothesis seems viable, the geologic evidence favors the geothermal mechanism. Erosion in the heavily cratered terrains of Mars tends to be spatially non-uniform (Gulick 1993, 1997a). Unlike fluvial valleys on Earth, valley systems on

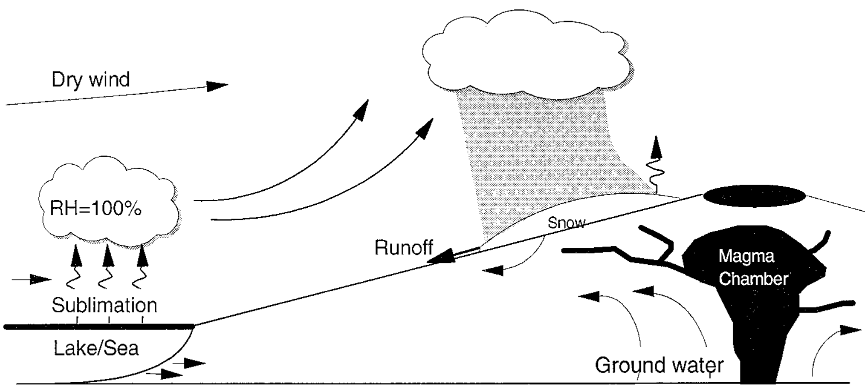

FIG. 13. Conceptual model of sublimating lake/sea/ocean mechanism. In this example, water vapor from a sublimating lake precipitates higher up on the flanks of a volcano where temperatures are cooler, forming a snowpack. Geothermal heating from an active volcano melts the base of the snowpack producing runoff and infiltration. Continued melting, runoff, and infiltration over time may result in the formation of fluvial valleys. The infiltrated water together with hydrothermally-driven upwardly moving groundwater may flow out to the surface farther down the flank and result in sapping.

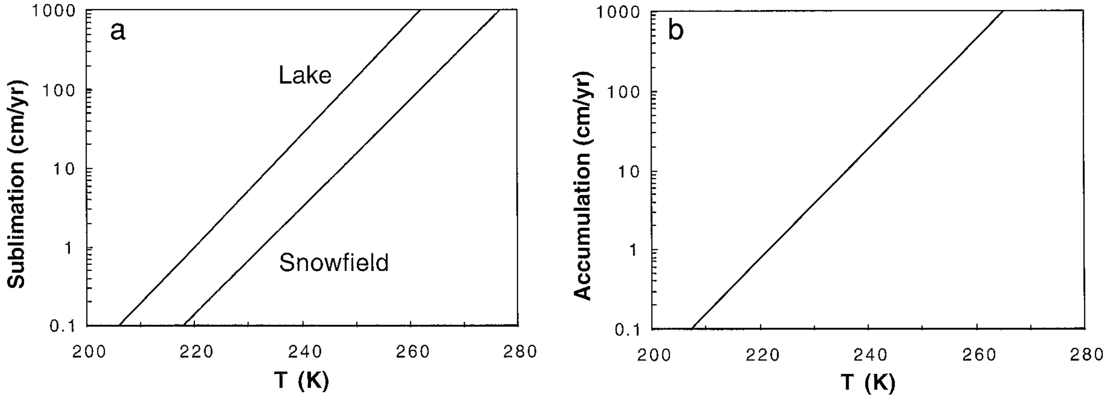

FIG. 14. Rates of sublimation of water from a frozen lake/sea/ocean and a snowfield lying 2 km above the body of water as a function of lake/sea temperature. Snowfield is cooler and thus experiences less sublimation. Rate of snow accumulation results from the difference between the body of water and snowfield sublimation. Larger elevation differences and warmer atmosphere (which hold more water) produce greater net snow accumulations.

Mars are typically separated by large expanses of undissected terrain of the same geological unit. An example of this is Warrego Valles (Gulick 1993, 1997a). This well-developed valley system is located along the southern boundary of the Thaumasia Plateau and probably supplies the best image for illustrating fluvial flow on the martian surface. At first glance the system convincingly looks like a terrestrial drainage system formed by rainfall. However, regions along the plateau boundary adjacent to Warrego Valles are not eroded by fluvial valleys and there are no indications that the adjacent terrain has been resurfaced.

The irregular pattern of erosion in the Warrego Valles region is particularly puzzling. Why should there be valley formation in one location and not in nearby regions? If the source of water for Warrego was rainfall, then adjacent areas along the plateau would have been similarly eroded, regardless of whether the valley system formed by runoff or sapping processes. This patchy distribution of fluvial features is in contrast to fluvial systems on Earth which tend to uniformly erode a given surface within a given climatic regime (Gulick 1993, 1997a, 1997b).

Assuming that snowfall was uniform in the heavily cratered terrain, the solar snowmelt hypothesis would predict uniform erosion on a given terrain unit, particularly in areas of similar lithology, relief, and slope aspect. Uniformly distributed erosion would not be expected in areas where these parameters are different since the amount of solar insolation on a given surface would likewise vary. However, the geothermal mechanism predicts that the snowmelt would only be generated in regions where the geothermal gradient was significantly larger than the background, for example, in regions near young impact craters, recent igneous intrusions, or active volcanoes. The snow would melt and erosion would result only in those localized areas. In the remaining areas, little to no erosion would result, because snow would eventually sublimate after the loss of the sea or ocean. Melting by geothermal heating seems to be consistent with the pattern of erosion on many geological surfaces on Mars, including along the southern boundary of Thaumasia Plateau on which Warrego Valles formed. In addition, the radial drainage pattern of Warrego Valles suggests that the valley system formed on a region of localized uplift. This uplift may have been produced by a subsurface magma intrusion (Gulick 1993, 1997a). Conversely, the solar snowmelt mechanism cannot explain the formation of Warrego Valles.

Periglacial and possible glacial landforms are also common on Mars. Given sufficient snowfall, the formation of these features would require less extensive melting than the fluvial features. However formation of the sinuous ridges interpreted as eskers (Kargel and Strom 1992, Baker *et al.* 1991) would require some basal melting. Either the solar or geothermal melting mechanisms would be consistent with these observed landforms.

VI. OCEAN LIFETIME

Given the enhanced water vapor transport rates caused by the transient greenhouse, what is the lifetime of the frozen sea? Baker *et al.* (1991) estimated total ocean volumes equal to several 10^7 km^3 with an average depth of roughly 1 to 2 km. Assuming present mean global temperatures of about 220 K, on the order of a centimeter of water vapor per year should sublimate from a frozen body of water. Given these initial conditions, the ocean would completely sublimate in several 10^5 years. If mean global temperatures increased to 240 or 250 K, sublimation rates would rise to approximately 10 and 100 cm/year, respectively, and the ocean would sublimate completely in 10^3 or 10^4 years. However, because these oceans would cover most of the Northern plains, spanning latitudes from 0° to 90°N (Baker *et al.* 1991, Parker *et al.* 1991), actual sublimation rates would vary significantly across the ocean's surface. In our model, we find the equatorial and polar latitude temperatures deviate 5 to 10 K from mean global temperatures. Therefore, depending on latitude, ocean lifetimes can vary as much as two orders of magnitude between the equator and the poles. In addition, Moore *et al.* (1995) concluded that ocean surface temperatures are very sensitive to albedo variations. Therefore, assuming a reasonable albedo range of 0.3–0.6 for sea ice, variations in albedo can affect ocean lifetimes by as much as an order of magnitude.

Regardless of the uncertainties involved in calculating ocean lifetimes, the ocean persists for a shorter period than the enhanced greenhouse. Any decrease in the surface area of the ocean or other body of water on the planet's surface will tend to slow the decline of the period of enhanced greenhouse. This is because the rate at which CO_2 weathers out of the atmosphere is assumed to be sensitive to the area of available surface water. As water coverage varies between 5 and 27%, the period of enhanced greenhouse varies by nearly an order of magnitude.

The water deposited at higher elevations could, however, return to the ocean. Water produced from melting basal layers of snow packs located in geothermally active regions would infiltrate and recharge subsurface aquifers, particularly along the perimeter of such areas. This recharge could be rapid given Mars' presumed unusually high subsurface permeabilities (Carr 1979). Furthermore, if the hydraulic and thermal pathways that triggered the initial formation of the outflow channels still existed, then it is possible that more than one ocean-forming event could have occurred within the same greenhouse period. Multiple episodes of outflow channel formation are consistent with the geological record (Chapman and Scott 1989, Rotto and Tanaka 1991).

One ocean-forming event may not have provided the duration of precipitation required for significant fluvial valley formation on typical land surfaces. However, valleys might have formed quickly on highly erodable sediment or ash surfaces. Even if valleys did not result during a single ocean period, resulting meltwater would have replenished groundwater reserves in geothermally active regions such as Tharsis and Elysium. Such recharged groundwater systems might then have been capable of forming valleys.

Therefore, direct precipitation from a sublimating sea or ocean does not need to last as long as it takes to form valleys. The sublimating sea or ocean provides a mechanism to cycle water vapor from the Northern Lowlands back to the Southern Highlands, where it accumulates as snow in high elevation regions. Vigorous geothermal activity would melt basal layers of snowpacks and any underlying permafrost. Geothermal melting would provide a pathway for the snowmelt to recharge the underlying aquifer system.

Fluvial valleys on Earth normally form in approximately 10^5 years or more (Gulick 1993, 1997a) while the ocean may only have lasted on the order of several 10^3 to several 10^4 years. Ocean volumes estimated by Baker *et al.* are roughly 3 orders of magnitude higher than that required to form well-developed valley systems in the heavily cratered terrains (e.g., Warrego Valles and Parana Valles) or on the volcanoes (Gulick 1993, 1997a). Therefore, empirically, the ocean does contain enough water to form valleys on Mars. The higher than average evaporation rates in the equatorial regions would have accelerated erosion rates early in the formation of fluvial valleys helping to establish drainage pathways. Subsequent meltwater would concentrate in these drainages and aid in valley enlargement. Higher rates of snow accumulation would help to quickly recharge subsurface aquifers in regions of geothermal activity where infiltration exceeds surface runoff.

In summary, in high elevation areas where the surface is easily eroded and hydrothermally active, such as on the flanks of an ash-covered volcano, fluvial valleys can form initially by surface runoff processes as geothermal heat melts the base of the snowpack. As meltwater continues to infiltrate, aquifers become recharged, and water tables start to rise, groundwater sapping processes can then play a dominant role in enlarging the valley system. This sort of scenario may help to explain why fluvial valleys on martian volcanoes do not exhibit pronounced structural control as is common with terrestrial sapping valleys but do exhibit other characteristics common to sapping valleys. Such a morphology is also common on the Hawaiian volcanoes where fluvial valleys initially form largely by runoff processes but then become significantly enlarged as valley floors intersect the underlying aquifer system and exhibit other characteristics common to valley formation by groundwater sapping processes.

VII. CONCLUSION

We have explored whether pulses of CO_2 released into the martian atmosphere can modify the climate and produce episodes of geomorphologic change. The conditions under which such a mechanism may operate are summarized below.

First, large pulses of CO_2 must be released into the atmosphere. For this work, we assume that the Baker *et al.* (1991) hypothesis is correct: the formation of the outflow channels was coincident with the release of large amounts of CO_2 into the atmosphere. Regardless of the specific mechanism, the pulse hypothesis clearly requires large inventories of readily releasable CO_2 on Mars, particularly if multiple pulses are postulated. While estimates of Mars' total CO_2 inventory range up to 5 bar, it is not clear what processes might sequester a large fraction of this CO_2 into such reservoirs.

Once released, large pulses of CO_2 can indeed substantially affect the global climate. Guided by our modeling of atmospheric water vapor transport, we define "substantial" as those model cases in which global temperatures remain above 240 to 250 K for periods longer than 10^6 years. Fluvial erosion can result in such circumstances. Such cases must also produce a modern climate which is consistent with the currently observed atmospheric conditions on Mars. Pulses of at least 2 bar of CO_2 injected at 3 Ga and of no more than 1 bar at 1 Ga satisfy both constraints.

The length of time the atmosphere remains above a given temperature is primarily controlled by the size of the ocean. Larger bodies of water result in faster weathering rates and a shorter duration of greenhouse conditions. For example, global temperatures remain above 240 K only half as long when water covers 20% of Mars' surface area as when water covers only 10%. Global temperatures also play a role. The decline of the thick atmosphere is more rapid at 2 Ga than at 1 Ga when the solar luminosity is greater. The size of the CO_2 pulse itself has less influence on the duration of the warm epoch. Weathering rates for the case of 5% water coverage are not sufficient at 1 and 2 Ga to allow the climate to collapse and polar caps to form by the present day. Indeed the relatively large bodies of water (10, 20, and 27% water coverage) favored by Baker *et al.* (1991) are capable of removing the CO_2 required to produce a warm climate. As it postulates both large bodies of water and large pulses of CO_2, the Baker *et al.* hypothesis is thus consistent with the currently observed Mars.

The second requirement on the CO_2 pulse hypothesis is that there be a mechanism to supply water to sites of observed erosion. Such a source is required since even globally warmer temperatures do not, in and of themselves, result in erosion. Either hydrothermal cycling of groundwater to the surface or an atmospheric hydrologic cycle is required.

The outflow channel discharges themselves, present as a frozen sea or ocean, might provide the atmospheric water source. Water vapor sublimated off the frozen surface can be transported to higher altitudes, where it would fall as snow. An efficient system could produce up to 100 cm/year of snowfall from such a frozen sea, although more realistic models would produce less precipitation. For this mechanism to be viable, regular winds must consistently carry a substantial quantity of water to specific, localized regions. Geologically significant transport and fluvial or glacial erosion will only occur when mean atmospheric temperatures remain greater than about 240 to 250 K for tens of millions of years. We find that only CO_2 pulses of several bars can produce such transient conditions.

The ocean itself may completely sublimate well before the decline of the enhanced greenhouse period. Whether or not the early decline of the ocean affects the duration of the greenhouse epoch depends upon the fate of the water. If it is simply redistributed to the surface at higher elevations, there would be relatively little impact. If the sublimated water ultimately infiltrates the surface at high elevations, then the return to initial atmospheric temperature and pressure conditions could take longer. However, if the hydraulic and thermal pathways required for outflow channel formation still existed, then more than one ocean-forming event might have occurred during the period of enhanced greenhouse. In this scenario, the time before atmospheric collapse would likely be similar to our model results.

The third requirement of the pulse hypothesis is a mechanism to melt the snowpack. Either localized regions of increased geothermal heat flow or incident solar radiation can serve this purpose. However, localized geothermal activity is more compatible with the localized nature of martian fluvial valleys.

In summary, we conclude that episodic greenhouse climates that raised global temperatures over 240 to 250 K for periods greater than about 10^6 years are capable of producing fluvial valleys and glaciers at higher elevations if there exists a sufficient source of surface water, such as a frozen sea or ocean. Subsequent melting of resulting snowpacks could have been provided by localized geothermal activity or possibly by seasonal warming. The sublimating ocean provides a mechanism by which water deposited into the Northern Plains by the outflow channels can return to the higher elevation Southern Highlands. If water can infiltrate back into subsurface aquifers, such a process could potentially close the loop in the hydrological cycle on Mars, allowing groundwater which flows out to the surface and into the Northern Lowlands to return to upland areas to begin the cycle again.

Given the uncertainties in the lifetime of a single sea or ocean, it is not clear whether the ocean would last long enough for fluvial valley formation by direct precipitation and snowmelt. However, rapid snow accumulation and subsequent melting in regions of vigorous geothermal activity would recharge highland aquifers and allow valley formation to continue by groundwater sapping driven by hydrothermal circulation (Gulick 1993, 1997b). Episodic ocean formation may cause the martian climate to alternate between warm and cool conditions as carbonate formation removes CO_2 from the system.

Models that satisfy all constraints are those with CO_2 pulses in excess of 2 bar at 3 Ga, 1 bar at 2 Ga, and nearly 1 bar at 1 Ga. However, given the uncertainties in these simulations, the 0.5 bar pulse at 1 Ga may also satisfy the constraint as the peak equatorial temperatures just reach 240 K.

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