



HAL
open science

Scenario for the evolution of atmospheric pCO₂ during a snowball Earth

Guillaume Le Hir, Gilles Ramstein, Yannick Donnadiou, Yves Godd ris

► **To cite this version:**

Guillaume Le Hir, Gilles Ramstein, Yannick Donnadiou, Yves Godd ris. Scenario for the evolution of atmospheric pCO₂ during a snowball Earth. *Geology*, 2008, 36 (1), pp.47-50. 10.1130/G24124A.1 . hal-02902761

HAL Id: hal-02902761

<https://hal.science/hal-02902761>

Submitted on 18 Dec 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destin e au d p t et   la diffusion de documents scientifiques de niveau recherche, publi s ou non,  manant des  tablissements d'enseignement et de recherche fran ais ou  trangers, des laboratoires publics ou priv s.

Scenario for the evolution of atmospheric $p\text{CO}_2$ during a snowball Earth

Guillaume Le Hir
Gilles Ramstein
Yannick Donnadieu } UMR CEA/CNRS/UVSQ, 1572 Laboratoire des Sciences du Climat et de l'Environnement, CE Saclay,
Orme des Merisiers, Bât. 701, 91191 Gif sur Yvette Cedex, France
Yves Godd ris UMR CNRS, 5563 Laboratoire des M canismes et Transferts en G ologie, Observatoire Midi-Pyr n es,
14, avenue Edouard Belin, 31400 Toulouse, France

ABSTRACT

The snowball Earth theory, initially proposed by J.L. Kirschvink to explain the Neoproterozoic glacial episodes, suggests that the Earth was globally ice covered at 720 Ma (Sturtian episode) and 640 Ma (Marinoan episode). The reduction of the water cycle and the growth of large ice sheets led to a collapse of CO_2 consumption through continental weathering and biological carbon pumping. As a consequence, atmospheric CO_2 built up linearly to levels allowing escape from a snowball Earth. In this contribution, we question this assumed linear accumulation of CO_2 into the atmosphere. Using a numerical model of the carbon-alkalinity cycles, we suggest that during global glaciations, even a limited area of open waters (10^3 km^2) allows an efficient atmospheric CO_2 diffusion into the ocean. This exchange implies that the CO_2 consumption through the low-temperature alteration of the oceanic crust persists throughout the glaciation. Furthermore, our model shows that rising CO_2 during the glaciation increases the efficiency of this sink through the seawater acidification. As a result, the atmospheric CO_2 evolution is asymptotic, limiting the growth rate of the atmospheric carbon reservoir. Even after the maximum estimated duration of the glaciation (30 m.y.), the atmospheric CO_2 is far from reaching the minimum deglaciation threshold (0.29 bar). Accounting for this previously neglected carbon sink, processes that decrease the CO_2 deglaciation threshold must be further explored.

Keywords: carbon cycle, seafloor weathering, snowball Earth, Neoproterozoic.

INTRODUCTION

Although processes and conditions required to trigger a snowball Earth (Kirschvink, 1992) have been intensively explored (Donnadieu et al., 2002, 2004a, 2004b; Schrag et al., 2002; Warren et al., 2002), studies related to the deglaciation of a snowball Earth remain scarce (Caldeira and Kasting, 1992; Higgins and Schrag, 2003; Pierrehumbert, 2005). The amount of atmospheric CO_2 needed to trigger the deglaciation from a globally ice-covered Earth was first evaluated at 0.12 bar (Caldeira and Kasting, 1992) and then modified at 0.29 bar by Pierrehumbert (2004) to account for the decreased solar luminosity in Neoproterozoic time. Using a more complex and comprehensive model (an atmospheric general circulation model, i.e., AGCM), Pierrehumbert (2005) demonstrated that the threshold value of 0.29 bar calculated with an energy balance model (EBM) was underestimated, and suggested that this value is at the lower end of the CO_2 levels required to deglaciate the snowball Earth.

In this contribution we focus on the various processes that may affect the way CO_2 would accumulate in a snowball atmosphere. It has been assumed that the drastic reduction of the continental weathering and the primary productivity occurring in a snowball Earth would have left the CO_2 outgassed by volcanoes free

to accumulate in the atmosphere. Hoffman et al. (1998) calculated that atmospheric $p\text{CO}_2$ would reach 0.12 bar at the present outgassing rate after ~ 4 m.y. if no air-sea gas exchange took place, but that partial gas exchange through cracks in sea ice would increase this estimate. In contrast, Higgins and Schrag (2003) assumed that the ocean and atmosphere were in equilibrium with respect to CO_2 due to the air-sea gas exchange during the entire glacial event. However, in this later case an important additional factor able to modify the seawater chemistry, i.e., the low-temperature alteration of the oceanic crust, has to be considered if air-sea gas exchange took place. Because a large amount of the atmospheric CO_2 could be dissolved into the ocean, the ocean acidification promotes the removal of carbon through basaltic crust dissolution. This sink may have moved the simple linear atmospheric CO_2 accumulation toward an asymptotic evolution, raising the question of whether deglaciation melting can be reached.

CARBON CYCLE AND SEAFLOOR WEATHERING DURING SNOWBALL EVENTS

To investigate and quantify the carbon cycle evolution in a snowball environment, we designed a simple numerical model of the

carbon-alkalinity cycles that includes the calculation of the seafloor weathering response to the acidification of the ocean (see Appendix). The model includes a box for the atmosphere, while the ocean is partitioned between a surface and a deep reservoir connected to a reservoir of water percolating through the oceanic crust, with a residence time of 2×10^4 yr (Elderfield and Schultz, 1996). The CO_2 exchange flux, F , at the ocean-atmosphere interface is calculated as a function of the gradient between the calculated atmospheric ($p\text{CO}_2^{\text{atm}}$) and dissolved oceanic $p\text{CO}_2$ ($p\text{CO}_2^{\text{ocean}}$):

$$F = \alpha (p\text{CO}_2^{\text{atm}} - p\text{CO}_2^{\text{ocean}}) \text{area}_{\text{open}}, \quad (1)$$

where α is the diffusion coefficient fixed at $16 \text{ mol}/(\text{yr m}^2 \text{ PAL})$ [Present Atmospheric Level] (Etcheto et al., 1991), a value typical of high-latitude cold seawater, and $\text{area}_{\text{open}}$ is the area of open water, a value considered as a model parameter that can be tested. $p\text{CO}_2^{\text{ocean}}$ is estimated using Henry's law, fixing surface ocean temperature at 275 K during the snowball Earth. Carbonate speciation is calculated for each water reservoir at each time step. We assume an oceanic vertical mixing 100 times lower than the present-day thermohaline circulation (0.02 Sv) between the surface and deep ocean to account for the maximal expected overturning reduction due to the ice-covered ocean, because it seems physically improbable to completely shut down the general circulation (Zhang et al., 2001). Low-temperature seafloor alteration is calculated using laboratory kinetic laws (see Appendix). The dissolution of each mineral constitutive of the fresh basaltic crust (assumed to be a tholeiitic basalt) is modeled as a function of the temperature, T , of the water in contact with the basalt (fixed at 40°C) (Brady and Gislason, 1997), and the pH of the percolating waters. The conclusions of this study partly depend on the model parameters, including the vertical mixing of the ocean, the present-day amplitude of the seafloor weathering, the water flux percolating the oceanic crust as well as its temperature, the seafloor spreading rate, the presence or absence of seafloor carbonates, and the area of open water. In the following we concentrate on the two last parameters, which are by far the most important. More details and

diagrams about sensitivity tests, regarding other important parameters such as the vertical mixing of the ocean and the efficiency of the seafloor weathering, can be found in GSA Data Repository Figures DR1 and DR2.¹

Efficient Exchange Between the Ocean and Atmosphere

We first tested the minimal surface of open waters allowing an efficient diffusion of the atmospheric CO₂ into the ocean. Patches of open water were proposed in the original snowball Earth theory as refugia for living organisms (Kirschvink, 1992). Their existence has been confirmed by the study of Neoproterozoic formations (Hoffman and Maloof, 1999). To test the efficiency of the CO₂ diffusion from the atmosphere into the ocean, we define the diffusion efficiency *E*:

$$E = 1 - \frac{p\text{CO}_2(\text{area}_{\text{open}})}{p\text{CO}_2(\text{hard snowball})}, \quad (2)$$

where $p\text{CO}_2(\text{area}_{\text{open}})$ is the CO₂ level reached after a simulation of 30 m.y., the maximum estimated duration of the snowball event (Hoffman et al., 1998), for a given free water area ($\text{area}_{\text{open}}$), and $p\text{CO}_2(\text{hard snowball})$ is the same value assuming an ocean fully covered with ice. This *E* parameter is then normalized to its present-day value ($\text{area}_{\text{open}} = 363 \times 10^6 \text{ km}^2$). In our set of model simulations, wherein the ice-free surface is varied from the present-day ocean surface ($363 \times 10^6 \text{ km}^2$) to 0 km², we calculate that above 3000 km², atmospheric CO₂ has enough time at the geologic time scale (here several millions of years) to dissolve within the ocean, and the area of open water is not a limiting factor for diffusion (Fig. 1). Below 3000 km², atmospheric CO₂ mixing into the ocean is limited. Today the surface of emerged active hydrothermal areas largely exceeds the 10³ km² scale, being equal to $1.5 \times 10^6 \text{ km}^2$ (Dessert et al., 2003). During global glaciations, emerged geothermal environments may be associated with small open water areas, maintained by heat production and lava flows. However, the existence of thick sea ice (Goodman, 2006) may reduce the contact between the patches of free waters and the whole ocean, limiting the CO₂ dissolution. For that reason, we cannot firmly state that the atmospheric CO₂ diffusion was fully efficient, but only 3000 km² of open waters in contact with the whole ocean are enough to achieve massive CO₂ dissolution.

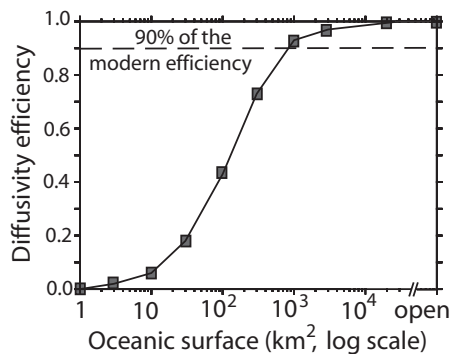


Figure 1. Normalized CO₂ diffusion efficiency as function of the ice-free oceanic surface.

Implications

If CO₂ is allowed to dissolve within the ocean during the building up of extremely high atmospheric carbon levels, seawater pH should drastically decrease and promote both deep-sea carbonates and oceanic basaltic crust dissolution.

Seafloor Weathering and Its Implication on the pCO₂

In the absence of deep seafloor sedimentary carbonates, the seawater acidification enhances the consumption of dissolved carbon through low-temperature alteration of the oceanic basaltic crust. Under the corrosive action of seawater percolating the crust at almost kilometeric depth, basalts dissolve and release alkalinity, which is then removed through carbonate precipitation in veins from highly saturated pore waters (Alt and Teagle, 1999; Brady and Gislason, 1997; Spivack and Staudigel, 1994). The CO₂ consumption through seafloor basaltic weathering rises until the ocean is sufficiently acidified, so that consumption of carbon through seafloor weathering balances solid Earth outgassing.

The question is whether this theoretical steady-state CO₂ is higher than the required deglaciation threshold. In our scenario accounting for seafloor weathering, the atmospheric CO₂ build up does not rise linearly as in the classical snowball scenario (Fig. 2), but reaches an asymptotic value. Assuming a present-day total degassing rate of $7.15 \times 10^{12} \text{ mol/yr}$ (a value fixed to balance the present continental silicate and seafloor basalt CO₂ consumption rates) (Brady and Gislason, 1997; Gaillardet et al., 1999), we found that the atmospheric partial pressure does not exceed 0.17 bar within the estimated snowball duration of 12 m.y. (Bodiseliitch et al., 2005), because the seawater pH goes rapidly down to 6, increasing the seafloor weathering rate by a factor slightly above 4. Even after 30 m.y., the maximal duration for the snowball event (Hoffman et al., 1998), and with a volcanic outgassing rate enhanced by 20% (which is the maximum increase recorded over the past

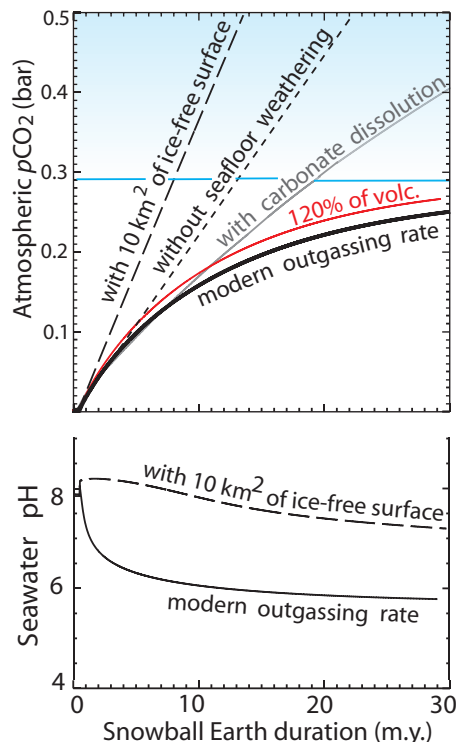


Figure 2. CO₂ evolution as function of the snowball Earth duration; 30 m.y. is maximum estimate. One run was performed with 10 km² of ice-free surface, all others with ice-free surface of 3000 km². Snowball earth deglaciation threshold (blue line) is 0.29 bar, estimated through an energy balance model simulation for a Neoproterozoic insolation. With a modern outgassing rate, the difference between the run with or without the seafloor weathering (black thick line and black dashed line, respectively) shows the impact of the CO₂ consumption by the low-temperature weathering of the basaltic seafloor. Higher volcanic degassing rate (red line) (1.2× present day; see text) would help at rising more rapidly the atmospheric CO₂ level but not sufficiently to overcome the deglaciation threshold. Because total degassing depends on the seafloor-spreading rate (Gaffin, 1987), the CO₂ consumption increases proportionally the surface of fresh seafloor basaltic rocks exposed to seawater. Below 10 km² of ice-free surface, the CO₂ diffusion becomes so weak that the atmosphere and ocean remain virtually isolated, the CO₂ accumulates in the atmosphere, and the seafloor weathering effect becomes negligible.

160 m.y.; Cogne and Humler, 2004), the CO₂ threshold of 0.29 bar required to escape the snowball glaciation cannot be reached (Fig. 2).

Buffering of Seawater pH through Carbonate Dissolution or Basaltic Weathering?

Seafloor sedimentary carbonate dissolution may have buffered seawater pH during the snowball glaciation, thus reducing the efficiency of seafloor weathering. However, maintain-

¹GSA Data Repository item 2008013, Figures DR1–DR3, supplementary information on the model and additional tests, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

ing carbonate saturation (Higgins and Schrag, 2003) under 0.12 bar of CO₂ would require a calcium concentration in seawater twice its present-day level, corresponding to the dissolution of 2.5×10^{19} mol of carbonates if preglacial calcium concentration was close to its present-day value. If carbonate were of shelfal origin (pelagic carbonate producers being virtually absent), and considering the maximum past carbonate shelf extent of 15×10^6 km² (Walker et al., 2002), this would correspond to the dissolution of 66 m of carbonate sediments. This value would be even greater since the 0.12 bar threshold is largely underestimated (Pierrehumbert, 2004). Because sea level fell by more than 400 m during the glacial event (Hoffman et al., 2007), these shelf carbonates might not be available for dissolution.

However, carbonate slumps along continental slopes (Swart, 1992) or preglacial direct abiotic precipitation might have partly overlaid the deep seafloor with carbonates. We tested this hypothesis by running the model assuming that deep-sea carbonate dissolution occurs kinetically during the glacial event, forcing the seawater saturation index to 1. This corresponds to the maximum impact of carbonate dissolution on seawater chemistry, since dissolution stops when the saturation index reaches 1. We found that alkalinity rose to 18 equivalents/m³ when CO₂ reached 0.29 bar, as a result of Ca²⁺ release by the carbonate dissolution and Ca²⁺/Mg²⁺ exchange at mid oceanic ridges (Elderfield and Schultz, 1996). Seawater pH is calculated as 6.17, close to the 5.9 calculated in the absence of seafloor sedimentary carbonates. However, oceanic crust dissolution is sensitive to small pH changes. We calculate that, accounting for the maximum effect of carbonate buffering and because basaltic seafloor weathering is reduced, 0.29 bar of CO₂ can be reached in 19 m.y. This maximum effect corresponds to the dissolution of a 3-m-thick sedimentary carbonate layer spread over the global seafloor surface.

A possible anoxic state of the deep ocean may increase the pH of seawater during the snowball Earth. This would also result in decreased efficiency of the seafloor weathering. All along the glacial state, sulfate reduction may have produced alkalinity if the deep ocean was anoxic. The importance of this process depends upon the SO₄²⁻ level in seawater prior to the glacial event, and upon the availability of organic carbon in the water column and on the deep seafloor. A recent estimation shows that the SO₄²⁻ level might have been an order of magnitude below the present-day level (Hurtgen et al., 2002), thus largely below the dissolved inorganic carbon content of a snowball ocean, itself an order of magnitude above its present-day level in our calculations due to efficient atmospheric carbon dissolution.

For that reason, we suggest that the ocean pH was still largely controlled by carbonate speciation, even during a snowball event.

CONCLUSION

If the snowball Earth occurred, it must have deglaciated. Our study shows that if the area of surface water in contact with the deep ocean is sufficient, the dissolution of the basaltic oceanic crust during the snowball glaciation may delay the atmospheric CO₂ rise required to reach the melting threshold, up to unacceptable time spans. The snowball theory thus requires either an extremely efficient dissolution of a large seafloor sedimentary carbonate reservoir whose existence remains hypothetical, or additional plausible processes able to decrease the CO₂ threshold through, for example, an albedo decrease, such as the deposition of dark fine volcanic ash on the ice and snow as suggested by Pierrehumbert (2004), or the existence of a thin equatorial ice (Goodman, 2006; Pollard and Kasting, 2005, 2006; Warren and Brandt, 2006).

APPENDIX: GEOCHEMICAL MODELING PROCEDURE

To simulate the evolution of the carbon content before the global glaciation, we first run the model according to Proterozoic preglacial conditions until a steady state is reached (Fig. DR3; see footnote 1). We use a standard silicate weathering law, where Ca²⁺ and Mg²⁺ weathering rates are proportional to global runoff and depend on mean global air temperature (Oliva et al., 2004). Continental carbonate weathering is proportional to global runoff times the concentration of Ca²⁺ in equilibrium with calcite at the calculated mean air temperature and atmospheric CO₂. Both air temperature and runoff are assumed to be a function of atmospheric CO₂. Biological productivity in the surface ocean is made dependent on the input flux of phosphorus from the deep ocean (to simulate upwelling consequences) and from the weathering of continental surfaces. These dependencies are used for the calibration procedure, because continental silicate, carbonate, and phosphorus weathering are shut down during the snowball glaciation.

To apply snowball conditions we instantaneously shut down all continental weathering fluxes to reproduce the consequences of the rapid growth of continental ice sheets and the strong weakening of the hydrological cycle. Surface water temperature is forced to drop from 20 °C to 2 °C, and the vertical mixing between the surface and deep ocean decreases from 21×10^6 m³/s to 0.2×10^6 m³/s. The model then evolves freely.

The α value used in equation 1 depends on wind speed (Wanninkhof, 1992). The wind

action may be more efficient on one large surface than on several small. Since the total of ice-free surface is the sum of several small surfaces, K may be overestimated in our scenario. However in the extreme case wherein K is reduced by 10, the threshold surface required for an efficient exchange reaches 3×10^4 instead of 3×10^3 km², which remains very small. Note, however, that wind speed during the snowball event remains largely unknown, and the K we used is probably one of the best estimates that can be made.

Seafloor Weathering Parameterization

The deep ocean reservoir is in contact with a water reservoir incorporated into the oceanic crust. The temperature of the deep ocean is held constant at 275 K, and based on a present-day estimation (Elderfield and Schultz, 1996), the exchange water flux between the reservoir of percolating waters and the deep ocean is 0.2×10^6 m³/s, given that 735×10^{13} kg/yr of water are involved in the water circulation off axis at low temperature.

The reservoir of percolating waters is depleted in carbon through low-temperature dissolution of the basaltic crust, under the corrosive action of seawater. The release of alkalinity through this process is assumed to finally lead to the precipitation of carbonate minerals from highly saturated waters in veins, thus removing carbon from the ocean-atmosphere system at the million year time scale. The global sink of carbon is estimated as $\sim 1.5\text{--}2.4 \times 10^{12}$ mol/yr (Alt and Teagle, 1999). Dissolution of seafloor basalts is calculated using laboratory kinetic laws to estimate the response of the H⁺, OH⁻, and H₂O promoted dissolution to change in seawater pH. The mineralogical composition of the crust is taken as the mineralogy of a tholeiitic basalt, containing 54% labradorite, 32% diopside, 9% basaltic glass, 4.3% apatite, and 1.3% forsterite. Kinetic constants are taken from the WITCH model database (Godderis et al., 2006; Drever, 1997). For each mineral, the overall dissolution rate R_{basalt} (in moles of Ca²⁺ released per m² of mineral per year) is estimated as following:

$$R_{\text{basalt}} = \sum_i d_i \exp\left(\frac{-E_i}{R \cdot T_p}\right) C_i^{n_i}, \quad (\text{A1})$$

where the sum extends up to all the dissolving species (H⁺, OH⁻ and H₂O), while the index i stands for the dissolving species. E_i and d_i are, respectively, the activation energy and dissolution constant for each mineral depending on the species i promoted dissolution. T_p is the temperature of the percolating waters into the oceanic crust at which dissolution occurs, here fixed at 313 K. The value C_i stands for the concentration in the species i that promotes dissolution, while n_i is the order of the dissolution reaction. We assume that carbon consumption

through seafloor weathering (hereafter swf) equals half of the alkalinity released through dissolution. The calculated overall CO₂ consumption flux F_{swf} is multiplied by a constant area, representing the total mineral surface area exposed to dissolution:

$$F_{\text{swf}} = \text{SR} \cdot \text{area} \cdot R_{\text{basalt}}. \quad (\text{A2})$$

This constant is in fact a calibration constant that was fixed so that the total CO₂ consumption rate through seafloor weathering equals 1.6×10^{12} mol/yr under present-day conditions, within the lower range of recent estimations (Alt and Teagle, 1999; Spivack and Staudigel, 1994). SR is the seafloor spreading, normalized to its present-day value. It is kept constant at 1 in all simulations, except when assuming higher outgassing rate, itself corresponding to a higher seafloor-spreading rate. This overall kinetic formalism predicts a minimal basaltic dissolution rate at the present value of the ocean pH of 8.2.

ACKNOWLEDGMENTS

This work was supported by the ECLIPSE program (Environnement et Climat du Passé: Histoire et Evolution) of the Institut National des Sciences de l'Univers (INSU) of the French Centre National de la Recherche Scientifique (CNRS). We thank G. Halverson and P. Regnier for comments and corrections of this manuscript, and P. Sepulchre for his help and encouraging comments. Constructive comments by S. Warren, P. Hoffman, and anonymous reviewers helped to improve the manuscript.

REFERENCES CITED

- Alt, J.C., and Teagle, D.A.H., 1999, The uptake of carbon during alteration of ocean crust: *Geochimica et Cosmochimica Acta*, v. 63, p. 1527–1535, doi: 10.1016/S0016-7037(99)00123-4.
- Bodiselsch, B., Koeberl, C., Master, S., and Reimold, W.U., 2005, Estimating duration and intensity of Neoproterozoic snowball glaciations from Ir anomalies: *Science*, v. 308, p. 239–242, doi: 10.1126/science.1104657.
- Brady, P.V., and Gislason, S.R., 1997, Seafloor weathering controls on atmospheric CO₂ and global climate: *Geochimica et Cosmochimica Acta*, v. 61, p. 965–973, doi: 10.1016/S0016-7037(96)00385-7.
- Caldeira, K., and Kasting, J.F., 1992, Susceptibility of the early Earth to irreversible glaciation caused by carbon dioxide clouds: *Nature*, v. 359, p. 226–228, doi: 10.1038/359226a0.
- Cogne, J.P., and Humler, E., 2004, Temporal variation of oceanic spreading and crustal production rates during the last 180 My: *Earth and Planetary Science Letters*, v. 227, p. 427–439, doi: 10.1016/j.epsl.2004.09.002.
- Dessert, C., Dupre, B., Gaillardet, J., Francois, L.M., and Allegre, C.J., 2003, Basalt weathering laws and the impact of basalt weathering on the global carbon cycle: *Chemical Geology*, v. 202, p. 257–273, doi: 10.1016/j.chemgeo.2002.10.001.
- Donnadieu, Y., Ramstein, G., Fluteau, F., Besse, J., and Meert, J., 2002, Is high obliquity a plausible cause for Neoproterozoic glaciations?: *Geophysical Research Letters*, v. 29, 23, doi: 10.1029/2002GL015902.
- Donnadieu, Y., Godderis, Y., Ramstein, G., Nedelec, A., and Meert, J., 2004a, A 'snowball Earth' climate triggered by continental break-up through changes in runoff: *Nature*, v. 428, p. 303–306, doi: 10.1038/nature02408.
- Donnadieu, Y., Ramstein, G., Fluteau, F., Roche, D., and Ganopolski, A., 2004b, The impact of atmospheric and oceanic heat transports on the sea-ice-albedo instability during the Neoproterozoic: *Climate Dynamics*, v. 22, p. 293–306, doi: 10.1007/s00382-003-0378-5.
- Drever, J.I., 1997, *The geochemistry of natural waters* (third edition): Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 436 p.
- Elderfield, H., and Schultz, A., 1996, Mid-ocean ridge hydrothermal fluxes and the chemical composition of the ocean: *Annual Review of Earth and Planetary Sciences*, v. 24, p. 191–224, doi: 10.1146/annurev.earth.24.1.191.
- Etcheto, J., Boutin, J., and Merlivat, L., 1991, Seasonal-variation of the CO₂ exchange coefficient over the global ocean using satellite wind-speed measurements: *Tellus*, ser. B, *Chemical and Physical Meteorology*, v. 43, p. 247–255, doi: 10.1034/j.1600-0889.1991.00017.x.
- Gaffin, S., 1987, Ridge volume dependence on seafloor generation rate and inversion using long-term sealevel change: *American Journal of Science*, v. 287, p. 596–611.
- Gaillardet, J., Dupre, B., Louvat, P., and Allegre, C.J., 1999, Global silicate weathering and CO₂ consumption rates deduced from the chemistry of large rivers: *Chemical Geology*, v. 159, p. 3–30, doi: 10.1016/S0009-2541(99)00031-5.
- Godderis, Y., Francois, L.M., Probst, A., Schott, J., Moncoulon, D., Labat, D., and Viville, D., 2006, Modelling weathering processes at the catchment scale: The WITCH numerical model: *Geochimica et Cosmochimica Acta*, v. 70, p. 1128–1147, doi: 10.1016/j.gca.2005.11.018.
- Goodman, J.C., 2006, Through thick and thin: Marine and meteoric ice in a "Snowball Earth" climate: *Geophysical Research Letters*, v. 33, p. L16701, doi: 10.1029/2006GL026840.
- Higgins, J.A., and Schrag, D.P., 2003, Aftermath of a snowball Earth: *Geochimica, Geophysics, Geosystems*, v. 4, doi: 10.1029/2002GC000403.
- Hoffman, P.F., and Maloof, A.C., 1999, Glaciation: The snowball theory still holds water: *Nature*, v. 397, p. 384, doi: 10.1038/17006.
- Hoffman, P.F., Kaufman, A.J., Halverson, G.P., and Schrag, D.P., 1998, A Neoproterozoic snowball earth: *Science*, v. 281, p. 1342–1346, doi: 10.1126/science.281.5381.1342.
- Hoffman, P.F., Halverson, G.P., Domack, E.W., Husson, M.H., Higgins, J.A., and Schrag, D.P., 2007, Are basal Ediacaran (635 Ma) post-glacial "cap-dolostones" diachronous?: *Earth and Planetary Science Letters*, v. 258, p. 114–131.
- Hurtgen, M.T., Arthur, M.A., Suits, N.S., and Kaufman, A.J., 2002, The sulfur isotopic composition of Neoproterozoic seawater sulfate: Implications for a snowball Earth?: *Earth and Planetary Science Letters*, v. 203, p. 413–429, doi: 10.1016/S0012-821X(02)00804-X.
- Kirschvink, J.L., 1992, Late Proterozoic low-latitude glaciation: The snowball earth, *in* Schopf, J.W., and Klein, C., eds., *The Proterozoic biosphere*: Cambridge, Cambridge University Press, p. 51–52.
- Oliva, P., Dupre, B., Martin, F., and Viers, J., 2004, The role of trace minerals in chemical weathering in a high-elevation granitic watershed (Estibère, France): Chemical and mineralogical evidence: *Geochimica et Cosmochimica Acta*, v. 68, p. 2223–2243, doi: 10.1016/j.gca.2003.10.043.
- Pierrehumbert, R.T., 2004, High levels of atmospheric carbon dioxide necessary for the termination of global glaciation: *Nature*, v. 429, p. 646–649, doi: 10.1038/nature02640.
- Pierrehumbert, R.T., 2005, Climate dynamics of a hard Snowball Earth: *Journal of Geophysical Research*, v. 110, D01111, doi: 10.1029/2004JD005162.
- Pollard, D., and Kasting, J.F., 2005, Snowball Earth: A thin-ice solution with flowing sea glaciers: *Journal of Geophysical Research-Oceans*, v. 110, C07010, doi: 10.1029/2004JC002525.
- Pollard, D., and Kasting, J.F., 2006, Snowball Earth: A thin-ice solution with flowing sea glaciers: Reply: *Journal of Geophysical Research-Oceans*, v. 111.
- Schrag, D.P., Berner, R.A., Hoffman, P.F., and Halverson, G.P., 2002, On the initiation of a snowball Earth: *Geochimica, Geophysics, Geosystems*, v. 3, doi: 10.1029/2001GC000219.
- Spivack, A.J., and Staudigel, H., 1994, Low-temperature alteration of the upper oceanic crust and the alkalinity budget of seawater: *Chemical Geology*, v. 115, p. 239–247, doi: 10.1016/0009-2541(94)90189-9.
- Swart, R., 1992, Facies analysis of Late Proterozoic carbonate turbidites in the Zerrissene Basin, Damara-Orogen, Namibia: *Journal of African Earth Sciences*, v. 14, p. 283–294, doi: 10.1016/0899-5362(92)90105-L.
- Walker, L., Wilkinson, B.H., and Ivany, L.C., 2002, Continental drift and Phanerozoic carbonate accumulation in shallow-shelf and deep-marine settings: *Journal of Geology*, v. 110, p. 75–87, doi: 10.1086/324318.
- Wanninkhof, R., 1992, Relationship between wind-speed and gas-exchange over the ocean: *Journal of Geophysical Research-Oceans*, v. 97, p. 7373–7382.
- Warren, S.G., and Brandt, R.E., 2006, Snowball earth: A thin-ice solution with flowing sea glaciers: Comment: *Journal of Geophysical Research-Oceans*, v. 111, C09016, doi: 10.1029/2005JC003411.
- Warren, S.G., Brandt, R.E., Grenfell, T.C., and McKay, C.P., 2002, Snowball Earth: Ice thickness on the tropical ocean: *Journal of Geophysical Research-Oceans*, v. 107, no. C10, 3167, doi: 10.1029/2001JC001123.
- Zhang, R., Follows, M.J., Grotzinger, J.P., and Marshall, J., 2001, Could the Late Permian deep ocean have been anoxic?: *Paleoceanography*, v. 16, p. 317–329, doi: 10.1029/2000PA000522.

Manuscript received 29 May 2007

Revised manuscript received 30 August 2007

Manuscript accepted 31 August 2007

Printed in USA