phy, orientation, and motion. Specific information processing for motion is known not to take place in the primary visual cortex but rather in higher cortical regions such as the mediotemporal area (*10*, *11*). The closely related medial superior temporal area (*12*) processes optical flow images generated as one moves in three-dimensional space (the objects in such images seem to expand as one approaches them but contract as one moves away). The cells in these areas are highly sensitive to direction, and they act reciprocally through feedback pathways that connect with the V1 region of the primary visual cortex (*13*).

At this point, the encoding of spatial cues by V1 neurons and those of the primary somatosensory cortex seems to correlate well with perception (*1*, *6*) when no higher order sensory features (such as motion) are involved. However, the different findings of Chen *et al*. and Whitney *et al*. demonstrate clearly that perception of cues other than position may not be related to V1 activity (*2*, *8*, *9*). Encoding of position cues in the V1 region may be more flexible than generally accepted and is apparently subject to modulation by compensation (*2*) or suppression (*8*) of the perceived illusions mediated by feedback signals.

With the help of illusions, neuroscience is beginning to bridge the gap between psychology and the psychophysics of perception on the one hand and brain activity on the other. The question of whether brain activity in the primary somatosensory or visual cortex represents a truthful mirror of physical input or an image of perception cannot be answered by a simple "yes" or "no." The answer depends on the sensory system investigated and the stimulus used. In many cases, the image of the world within the brain is congruent with neither the "real" nor the perceived world. Illusions have been used as tools to understand the brain for more than 100 years, as exemplified by the work of the 19th-century psychophysicist Hermann von Helmholtz (*14*). It is only recently, however, that illusions have been exploited to elucidate the cortical representations of sensory stimuli and to localize the brain regions where real stimuli turn into perceptions (*1*, *2*, *6*, *8*, *9*).


**References**

1. L. M. Chen, R. M. Friedman, A. W. Roe, *Science* **302**, 881 (2003); published online 18 September 2003 (10.1126/science.1087846).
2. D. Whitney *et al.*, *Science* **302**, 878 (2003); published online 18 September 2003 (10.1126/science.1087839).
3. A. Grinvald *et al.*, *Nature* **324**, 361 (1986).
4. W. Penfield, T. Rasmussen, *The Cerebral Cortex of Man* (Macmillan, New York, 1950).
5. J. H. Kaas *et al.*, *Science* **204**, 521 (1979).
6. S. L. Macknik, M. M. Haglund, *Proc. Natl. Acad. Sci. U.S.A.* **96**, 15208 (1999).
7. R. B. Tootell, M. S. Silverman, E. Switkes, R. L. De Valois, *Science* **218**, 902 (1982).
8. R. von der Heydt, E. Peterhans, G. Baumgartner, *Science* **224**, 1260 (1984).
9. B. M. Ramsden, C. P. Hung, A. W. Roe, *Cereb. Cortex* **11**, 648 (2001).
10. J. H. R. Maunsell, D. C. van Essen, *J. Neurophysiol.* **49**, 1127 (1983).
11. J. A. Movshon, W. T. Newsome, *J. Neurosci.* **16**, 7733 (1996).
12. H. Saito *et al.*, *J. Neurosci.* **6**, 145 (1986).
13. D. J. Felleman, D. C. van Essen, *Cereb. Cortex* **1**, 1 (1991).
14. N. Wade, *Helmholtz's Treatise on Physiological Optics* (Thoemmes Continuum, Bristol, UK, 2000).


OCEAN SCIENCE

# Who Threw That Snowball?

**David Archer**

The geological record of Earth's climate resembles Arthur Conan Doyle's curious incident of the dog that didn't bark in the night (*1*). The Sun grows hotter with time, yet the temperature at Earth's surface does not leave the narrow constraints of the melting and boiling points of water—at least not for long. It seems that the dog did whimper during a period known as Snowball Earth, when much of Earth's surface appears to have been frozen. This episode occurred in the Neoproterozoic (1000 to 540 million years ago), just before complex fossils emerged in the geological record (*2*).

Enhanced online at www.sciencemag.org/cgi/content/full/302/5646/791

It is not difficult to explain the overall stability of the climate record. The problem is explaining why the dog barked at all. On page 859 of this issue, Ridgwell *et al*. (*3*) argue that calcium carbonate ($CaCO_3$) precipitation played a key role. The present-day carbon cycle is stabilized by plankton that precipitate $CaCO_3$ in the open ocean. These organisms, coccolithophoridae and foraminifera, had not yet evolved in the Snowball days, and hence most $CaCO_3$ deposition in the ocean took place in coastal waters. This difference may have been crucial in the events that drove Earth into the Snowball state.

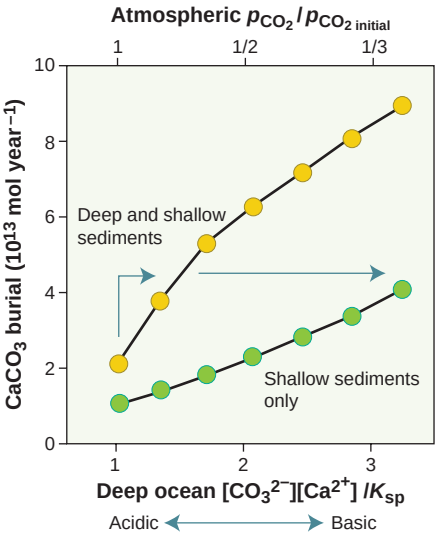
The overall stability of Earth's climate is generally attributed to a balance between degassing of $CO_2$ from deep within Earth, and consumption of $CO_2$ by weathering reactions at Earth's surface. Urey (*4*) wrote the reaction as

$$\underset{\text{metamorphosis}}{\text{CaSiO}_3 + \text{CO}_2 \longleftrightarrow \text{CaCO}_3 + \text{SiO}_2}$$
weathering

where the left-hand side is favored at the high temperatures of Earth's interior and the right-hand side is favored in the cool, wet conditions at Earth's surface. Walker *et al*. (*5*) proposed that the rate of weathering should depend on temperature and the intensity of the hydrological cycle, which in turn depend on the partial pressure of $CO_2$ in the atmosphere, $pCO_2$.The latter adjusts such that the $CO_2$ sources and sinks balance. If the Sun warms up, weathering accelerates, consuming more $CO_2$ until Earth's surface cools back down. The time scale of Walker *et al.*'s thermostat is ~500,000 years (*6*).

This thermostat appears to have broken down during Snowball Earth. The Snowball Earth hypothesis is based on geological evidence of multiple glaciations at sea level in low latitudes. The glaciation deposits are accompanied by "banded iron formations," which appear to mark the oxidation of an iron-rich anoxic ocean. They are overlain by caps of mineralogically peculiar $CaCO_3$ deposits that resemble abiotic precipitates from a highly supersaturated ocean.

The leading explanation for the Snowball is a runaway ice-albedo feedback. When ice




**Burial at sea.** Model sensitivity of global $CaCO_3$ to the saturation state, relative to the solubility $K_{sp} = [Ca^{2+}][CO_3^{2-}]$, for present-day conditions. Today, both open ocean and shallow $CaCO_3$ deposition occur (filled dots). If the present-day ocean had only shallow $CaCO_3$ deposition (open dots), a much larger change in ocean pH and atmospheric $pCO_2$ would be required to alter $CaCO_3$ burial.

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sheets reach some critical latitude, they reflect so much solar energy back into space that the entire planet freezes over. In the frozen world, weathering stops. Hydrothermal iron becomes more abundant than weathering sulfur in the anoxic ocean, generating the first banded iron formations on Earth in 1000 million years (*2*). Ultimately, Walker *et al.*'s thermostat overcomes the ice albedo, because $CO_2$ degassing from Earth's interior drives atmospheric $pCO_2$ upward. The ice melts abruptly, transforming Earth into a hothouse, which the thermostat eventually ameliorates. In the process, weathering consumes large amounts of $CO_2$, generating the cap carbonates.

There were two to four snowball glaciations during the Neoproterozoic (*7*). Why did the thermostat break repeatedly during this interval, but not at any other time? Ridgwell *et al.* have identified a mechanism that may help to answer this question. To understand their idea, we need to consider a second feedback mechanism in the carbon cycle: $CaCO_3$ compensation (*8*).

The balance this time is between weathering of $CaCO_3$ and its burial in the ocean. The homeostat switch is the pH of the ocean. $CaCO_3$ is a base and dissolves in acid. If the rate of weathering exceeds that of burial, the ocean becomes more basic, enhancing burial until the two fluxes balance. $CaCO_3$ compensation operates more quickly than Walker *et al.*'s thermostat; under today's conditions the time scale is about 10,000 years (*9*). Ridgwell *et al.* have identified a mechanism by which $CaCO_3$ compensation might have gone awry, drawing down enough $CO_2$ to explain the descent into the Snowball state.

The mechanism begins with a drop in sea level. When continental crust is partially flooded, as it is today, the ocean covers a large area of shallow-water sea floor. If the sea level drops by a few hundred meters, the area of shallow-water sea floor decreases dramatically, by about a factor of 10 in today's ocean. Today, such a sea-level drop would shift the burden of $CaCO_3$ deposition from the shallow to the deep ocean. This was not an option in the Neoproterozoic, when no organisms secreted $CaCO_3$ in the open ocean.

Ridgwell *et al.* (*3*) argue that deep-sea burial of $CaCO_3$ is more responsive to changes in ocean pH than shallow-water burial would be. $CaCO_3$ solubility increases with pressure. Today, the deep ocean straddles equilibrium (intermediate waters are supersaturated, whereas the abyss is undersaturated). Hence, a change in pH alters the boundary between supersaturated and undersaturated sea floor, driving a large change in $CaCO_3$ burial. In contrast, shallow waters are supersaturated almost everywhere. Shallow $CaCO_3$ burial can therefore only be enhanced by increasing the precipitation rate for $CaCO_3$, which requires a much larger pH change (see the figure).

Because the Neoproterozoic only had recourse to saturation state–insensitive shallow-water $CaCO_3$ deposition, a drop in sea level would have driven a larger excursion in ocean pH, and atmospheric $CO_2$, than would occur today. The mechanism identified by Ridgwell *et al.* (*3*) would still require an initial kick—perhaps a glaciation—to lower sea level, but would then amplify that cooling to within reach of the runaway ice-albedo feedback. In the aftermath of the Snowball, after Walker *et al.*'s thermostat melted the ice, the ocean would have relieved its $CaCO_3$ burden in newly flooded shallow seas, providing a complementary or alternative explanation for the observed cap carbonates.


**References**

1. A. C. Doyle, *Silver Blaze*, in *Strand Mag.* (December 1892).
2. P. F. Hoffman, D. P. Schrag, *Terra Nova* **14**, 29 (2002).
3. A. Ridgwell, M. J. Kennedy, K. Caldeira, *Science* **302**, 859 (2003).
4. H. C. Urey, *The Planets, Their Origin and Development* (Yale Univ. Press, New Haven, CT, 1952).
5. J. C. G. Walker, P. B. Hays, J. F. Kasting, *J. Geophys. Res.* **86**, 9776 (1981).
6. R. A. Berner, Z. Kothavala, *Am. J. Sci.* **301**, 182 (2001).
7. A. J. Kaufman, A. H. Knoll, G. M. Narbonne, *Proc. Natl. Acad. Sci. U.S.A.* **94**, 6600 (1997).
8. W. S. Broecker, T. H. Peng, *Global Biogeochem. Cycles* **1**, 15 (1987).
9. D. Archer, H. Kheshgi, E. Maier-Reimer, *Global Biogeochem. Cycles* **12**, 259 (1998).


CHEMISTRY

# Ionic Liquids—Solvents of the Future?

**Robin D. Rogers and Kenneth R. Seddon**

Research into ionic liquids is booming. The first industrial process involving ionic liquids was announced in March 2003, and the potential of ionic liquids for new chemical technologies is beginning to be recognized. The burgeoning interest in the field was obvious at the recent American Chemical Society (ACS) meeting in New York, where ionic liquids were the focus of 10 sessions (*1*).

Ionic liquids are composed entirely of ions. For example, molten sodium chloride is an ionic liquid; in contrast, a solution of sodium chloride in water (a molecular solvent) is an ionic solution. The term "ionic liquids" has replaced the older phrase "molten salts" (or "melts"), which suggests that they are high-temperature, corrosive, viscous media (like molten minerals). The reality is that ionic liquids can be liquid at temperatures as low as –96°C. Furthermore, room-temperature ionic liquids are frequently colorless, fluid, and easy to handle. In the patent and academic literature, the term "ionic liquids" now refers to liquids composed entirely of ions that are fluid around or below 100°C.

One of the primary driving forces behind research into ionic liquids is the perceived benefit of substituting traditional industrial solvents, most of which are volatile organic compounds (VOCs), with nonvolatile ionic liquids. Replacement of conventional solvents by ionic liquids would prevent the emission of VOCs, a major source of environmental pollution. Ionic liquids are not intrinsically "green"—some are extremely toxic—but they can be designed to be environmentally benign, with large potential benefits for sustainable chemistry (*2*).



**The BASIL reactor.** Upper phase, the solvent-free pure product; lower phase, ionic liquid.

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There are four principal strategies to avoid using conventional organic solvents: No solvent (heterogeneous catalysis), water, supercritical fluids, and ionic liquids. The solventless option is the best established, and is central to the petrochemical industry, the least polluting chemical sector. The use of water can also be advantageous, but many organic compounds are difficult to dissolve in water, and disposing of contaminated aqueous streams is expensive. Supercritical fluids, which have both gas- and liquid-like properties, are highly versatile solvents for

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