

## An Early Snowball Earth?

In their article "A Neoproterozoic snowball Earth" (Reports, 28 Aug., p. 1342), Paul F. Hoffman *et al.* report that global ice-house conditions existed during the Proterozoic, as inferred from negative carbon isotopes in carbonate rocks from Namibia. These conditions are said to have led to the near termination of life on Earth. In summary, the hypothesis suggests that global glaciation existed until volcanic outgassing increased carbon dioxide (CO<sub>2</sub>) concentrations to 120,000 parts per million of volume, at which time the global ice-house conditions collapsed. Several issues of geology and climate, however, remain unresolved.

First, how did global glacial conditions come about? Reduced solar forcing could not have been the cause, because the solar constant was lower before the breakup of the Rodinia supercontinent. A positive ice-albedo feedback triggered by reduced CO<sub>2</sub>

concentrations or high obliquity has been suggested (1). However, there are problems with both of these hypotheses.

It would have been difficult for the ocean to completely freeze because of its large thermal capacity and the wind-driven and thermohaline circulation. The equatorial ocean would have been buffered from sea ice by the high, year-round incident solar radiation at the surface, and therefore very thick ice would have needed to be present. Early studies of energy balance models suggest that a 5% reduction could generate a snowball Earth; however, more recent studies suggest that the solar forcing must be reduced by more than 10% to produce global glaciation by means of the ice-albedo feedback mechanism when large expanses of ocean exist (2). As for a high obliquity, there is no definitive evidence to suggest that Earth's obliquity was very different from that of the present or that high-latitude temperatures were warmer than those of low latitudes during the Neoproterozoic. Finally, there is evidence of low-latitude carbonates and evaporites along with glacial deposits during the late Proterozoic (3).

It would not have been possible for an idealized tropical supercontinent with fixed sea-surface temperatures (SSTs) (4) to maintain subfreezing temperatures on land, primarily because of the large quantity of solar radiation reaching the surface. Further snow-albedo feedback would not have been possible because moisture cannot penetrate the interiors of the supercontinent that would have allowed snow to accumulate, even if surface temperatures had been cold enough. It is possible that the results of Hoffman *et al.* indicate regional effects. The Congo Craton underwent significant changes between 700 and 600 million years ago as a result of a collision with East and West Gondwanaland (5). The Pan-African orogeny, which may have been of Himalayan proportions (6), could have produced alpine glaciers in the tropics. One possible hypothesis is that the collision led to a rapid draw down of CO<sub>2</sub> as a result of intense weathering because of its location in the deep tropics. Alpine glaciers then migrated to lower elevations.

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## Response

Jenkins and Scotese question the existence of a Neoproterozoic snowball Earth on the grounds of climate model simulations (1, 2) and suggest that the evidence from Namibia can be reinterpreted in terms of alpine glaciation associated with the tectonic assembly of Gondwana. Climate model results depend on prescribed boundary conditions.

Two of the studies (1) cited by Jenkins and Scotese are aimed at the "faint young sun" climatic paradox for the Archean Earth and prescribe a global ocean without continents. The other study (2), which appeared after our report in *Science*, addresses the problem of Neoproterozoic low-latitude glaciation on a supercontinent with a general circulation model (GCM). All of the models share a common trait, as does an earlier attempt to model Neoproterozoic low-latitude glaciation (3)—that changes in tropical SST are very small relative to changes in insolation (which are believed to have been lower in the past because of stellar evolution). In order to simulate the effect of a 5% reduction in the solar constant, Jenkins and Frakes (2) artificially reduced present-day monthly SSTs by 2°C at all latitudes. Given that tropical SSTs were actually 3° to 5°C colder than present at the last glacial maximum (21,000 years ago) (4), when the difference in insolation was less than 1%, there is good reason to question the prescribed response of SSTs to solar forcing in the models: in the Quaternary, the climatic response to orbital forcing was strongly amplified by changes in the levels of greenhouse gases (5). As the causal link between orbital forcing and greenhouse gas concentrations remains elusive, there are no grounds for its exclusion from Neoproterozoic climate change. In any event, it is hardly surprising that low-latitude glaciation does not occur in a GCM that has tropical SSTs prescribed only 2°C lower than present (2). Jenkins and

Frakes acknowledge (2) that "by prescribing SSTs we eliminate any possibility of "ice-house" conditions through a positive ice-albedo feedback at oceanic grid points." In their view, this constraint is justified "by the geologic rock record which does not indicate global glaciation during the Proterozoic or at any other period in Earth's history." We read the rock record differently.

An alpine glacial interpretation can be ruled out for reasons given in our original report: there were no mountains in the region at the time of the Ghaub glaciation. The glacial deposits occur within a broadly conformable succession of shelf carbonates, extending for more than 400 kilometers landward of the shelf edge where our study was conducted (6). Virtually all the glacial debris is from sources on the carbonate shelf. Mountains did form during the assembly of Gondwana, which involved the closure of oceans flanking the Congo Craton. Our study area, located on the southwestern salient of the craton, was directly affected by closure of the ocean to the west and south (present-day coordinates). The first deformation related to this closure [less than 550 million years ago (7)] folded the entire shelf carbonate suc-

cession enclosing the glacial deposits and clearly postdates the glaciation, which occurred 700 to 750 million years ago. The eastern ocean closed in two stages—680 million years ago and less than 550 million years ago (7), and the mountain belt related to its closure was located 1900 kilometers east of our study area. The dramatic rise in the ratio of strontium-87 to strontium-86 in the Neoproterozoic ocean that is commonly taken to signal an erosion flux associated with the Pan-African orogeny occurs only after the last of the proposed snowball glaciations—580 million years ago (8).

The snowball Earth hypothesis explains the most salient features of the Neoproterozoic sedimentary record, including low-latitude glaciations, banded iron-formations, cap carbonates, and carbon isotopic excursions, but Jenkins and Scotese offer no alternative explanation.

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