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2.3

Late Proterozoic Low-Latitude Global Glaciation: the Snowball Earth

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2.3.1 Introduction

A fundamental question of earth history concerns the nature of the Late Proterozoic glaciogenic sequences that are known from almost all of the major cratonic areas, including North America, the Gondwana continents, and the Baltic Platform. A major controversy involves the probable latitude of formation for these deposits – were they formed at relatively high latitudes, as were those of the Permian and our modern glacial deposits, or were many of them formed much closer to the equator? Arguments supporting a low depositional latitude for many of these units have been discussed extensively for the past 30 years (e.g., Harland 1964), beginning with the field observations that some of the diamictites had a peculiar abundance of carbonate fragments, as if the ice had moved over carbonate platforms. Indeed, many of these units, such as the Rapitan Group of the Canadian Cordillera, are bounded above and below by thick carbonate sequences which, at least for the past 100 Ma, are only known to have been formed in the tropical belt within about 33° of the equator (Ziegler et al. 1984). Other anomalies include dropstones and varves in the carbonates, as well as evaporites (for a complete review, see Williams 1975). Either the earth was radically different during the late Precambrian glacial episode(s), or the major continental land masses spent an extraordinary amount of time traversing back and forth between the tropics and the poles.

Paleomagnetic data have been invoked to both support and attack the low-latitude interpretations of these deposits (e.g., Harland 1964; Crawford and Daily 1971; Tarling 1974; McElhinny and Embleton 1976b; Morris 1977; Stupavsky et al. 1982; Embleton and Williams 1986). As discussed in Chapter 12, however, most of the earlier reported paleomagnetic data are not as convincing as they should be, particularly in terms of using geological tests to constrain the time at which remanent magnetization was acquired. Two important exceptions to this are the data of Embleton and Williams (1986) and of Sumner et al. (1987 and in prep.) for the varved sediments of the Elatina Formation of South Australia (discussed further in Chapter 12). During the uppermost Marionan glaciation in Australia, it now seems clear that these extensive, sea-level deposits (including varves and dropstones) were formed by widespread continental glaciers which were within a few degrees of the equator. The data are difficult to interpret in any fashion other than that of a widespread, equatorial glaciation.

A global climatic mechanism that could lead to such a widespread, low-latitude glaciation is not yet available. Williams (1975) suggested that, if the earth's obliquity reached angles higher than about 54°, the relative annual heat balance would shift so as to warm the poles more than the equator. Several arguments can be marshaled against this. First, although the obliquity of the earth varies by a few degrees with a period of a few tens of thousands of years (and hence is a component of Melankovitch cycles), the physical basis for the changes are fairly well understood. No mechanism is yet known that would lead to much larger oscillations of the sort proposed by Williams (1975). Although lack of a known mechanism should never be used alone to argue against the reality of an effect (e.g., continental drift), such an absence demands that the hypothesis receive especially critical scrutiny. Second, a redistribution of the radiant energy balance to polar latitudes should also move the carbonate belts from equatorial latitudes to the poles, where the glaciers (in Williams' model) should not encounter them. Finally, Vanyo and Awramik (1982, 1985), Awramik and Vanyo (1986), and Vanyo et al. (1986) argue convincingly that the obliquity 800 Ma ago was in the range of the present values, based on detailed studies of both modern and ancient heliotropic stromatolites.

2.3.2 Mechanisms Responsible for Low-Latitude Glaciation

It is necessary to consider an alternate, equally speculative mechanism that might yield widespread, low-latitude, sea-level glaciations, and perhaps help to interpret the last major episode of banded iron-formation deposition associated with it (Summer et al. in prep., and Sections 4.2 and 4.3). As discussed in Chapter 12, large portions of the continental land masses probably were within middle to low latitudes during the late Precambrian glacial episode, a situation that has not been encountered at any subsequent time in earth history. In a qualitative sense, this could have had a fundamental impact on global climate, as most of the solar energy adsorbed by the earth today is trapped in the tropical oceans (in contrast to the continents which are relatively good reflectors) and in high-latitude oceans which often have fog or other cloud cover. Furthermore, if extensive areas of shallow, epicontinental seas were within the tropics, a slight drop in sea level would convert large areas of energy-absorbing oceanic surface to highly reflective land surface, perhaps enhancing the glacial tendency. Escape from the "ice house" would presumably be through the gradual buildup of the greenhouse gas, CO_2, contributed to the air through volcanic emissions. The presence of ice on the continents and pack ice on the oceans would inhibit both silicate weathering and photosynthesis, which are the two major sinks for CO_2 at present (Section 4.7). Hence, this would be a rather unstable situation with the potential for fluctuating rapidly between the "ice house" and "greenhouse" states. A major question, of course, is whether the planet could get cold enough to permit the glaciers to advance to equatorial zones, without the poles reaching temperatures low enough to freeze the atmospheric CO_2 into dry ice, robbing the planet of the greenhouse rescue and yielding a permanent ice catastrophe.

Whatever the triggering mechanism, if the earth had normal obliquity during an equatorial glaciation we would expect that areas of high latitude would be at least as cold, if not colder, than the equator. A reasonable inference from this would be the presence of floating pack-ice over most of the ocean surface at middle to high latitudes, as well as glaciers on those land areas with larger net precipitation than sublimation or evaporation. Thus, the earth would have resembled a highly reflective "snowball". In this model, however, it is not clear what fraction of the equatorial oceans in deep water would form pack ice, as these zones would still absorb large amounts of the incident solar radiation, perhaps enough to prevent ice formation. Hence, we might expect to find some warm tropical "puddles" in the sea of ice, shifting slightly from north to south with the seasons. In turn, this should produce extreme climatic shifts in some local areas as envisioned by Williams and Tonkin (1985) and Williams (1986).

2.3.3 Implications of the Global Snowball Model

This global snowball model has several implications which might lend themselves to geological tests. First, it implies that the glacial units should be more or less synchronous (Harland 1964), and standard radiometric, paleomagnetic, paleontologic, or geochemical techniques should be capable of testing this concept. Second, Late Proterozoic strata from widely separate areas which preserve a record of these climatic fluctuations might bear an overall similarity in lithologic character, which would be a result of the global scale of the climatic fluctuations. Third, the presence of floating pack ice should reduce evaporation, act to decouple oceanic currents from wind patterns and, by inhibiting oceanic to atmosphere exchange of O_2, would enable the oceanic bottom waters to stagnate and become anoxic. Over time, ferrous iron generated at the mid-oceanic ridges or leached from the bottom sediments would build up in solution and, when circulation became reestablished toward the end of the glacial period, the iron could oxidize to form a "last-gasp" blanket of banded iron-formation deposition in upwelling areas. Iron-rich deposits of this sort are known from several late Precambrian glacial units in Canada, Brazil, Australia, and South Africa (Section 4.2). The banded iron-formations in the Rapitan Group of northern Canada are interbedded with tillites and contain occasional dropstones.

In closing, it is perhaps worth noting again that this Late Proterozoic glacial episode marks a major turning point in the evolution of life. Although preceded by abundant evidence of the presence of protists and prokaryotes (Sections 5.4, 5.5), it is followed by the first clear record of metazoan animals (the Ediacaran Fauna) and shortly thereafter by the appearance of mineralized fauna in the Cambrian (Chapters 7 and 8). It is tempting to extend the snowball earth speculation to suggest that these evolutionary changes were made possible by the glaciations – the periodic removal of all life from higher latitudes would create a series of post-glacial sweepstakes, perhaps allowing novel forms to establish themselves, free from the competition of a preexisting biota.

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