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The Neoproterozoic (1100–540 Ma) glacial intervals: No more snowball Earth?: Reply

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If scientists have learned anything in the last two decades it is that accurate ages of the magnetization (not just the rocks) are essential in order to avoid misinterpretations. Accurate ages of the magnetization are virtually unattainable for remagnetized rocks such as carbonates and non-red clastic sediments, both of which are very prone to remagnetization. For the Neoproterozoic glacial relicts, remagnetizations cannot be excluded and, in fact, are probable, with the only possible exception being the Elatina Formation, which forms the *casus belli* of the comment by Williams et al. [1]. In other words, our paper [2] attempted to emphasize that the paleomagnetic record for the Neoproterozoic glacial relicts is extremely poor, and that conclusions about low-latitude global glaciations are based on an unreliable database. Most of the comment by Williams et al. [1] is a verbatim repetition of the high-obliquity model found in other manuscripts and we will not deal with the many criticisms of that model, which can be found elsewhere [2–5].

Williams et al. [1] take us to task by noting that we present no new paleomagnetic data from glaciogenic rocks. However, their claim that *only paleolatitudes determined directly for glaciogenic rocks should be considered* actually weakens arguments in favor of low-latitude or global glaciation because precious few unambiguous paleomagnetic results are derived from these rocks! Williams et al. [1] make the claim that we have adopted an extreme stance by applying a uniformitarian model for the Neoproterozoic glaciations. If one adopts *ad-hoc* models on the basis of a single virtual geomagnetic pole (e.g., the Elatina Formation) or even a number of ill-defined paleomagnetic poles then indeed, a uniformitarian Earth is out of the question! We attempted to point this out in our paper [2] but will restate our case here.

The first point that any discussion regarding the Late Proterozoic glacial intervals must address is the paucity of reliable results from the glaciogenic rocks. Many of these results are transmitted and referenced in tables and data compilations without regard to the quality of the individual sample/site results. McWilliams and Kröner [6] presented arguments for *possible* low-latitude glaciations in South Africa based on data from the Neoproterozoic Nama Group. The 'primary' N1 remanence from those rocks has individual site α_{95} values that range between 29 and 55°! Most modern paleomagnetic researchers would reject these data outright. Certainly, the precision offered by these data do not lend confidence to conclusions regarding low-latitude glaciations. A second illustrative example is provided by the Port Askaig tillite in Scotland. This

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glaciogenic unit was studied paleomagnetically by Tarling [7] who concluded that the paleomagnetic data supported a low-latitude glaciation. However, Stupavsky et al. [8] clearly demonstrated the secondary nature of this remanence. Indeed, even the data obtained from the Sturtian Merinjina tillites of Australia [9] were complex and the mean directions were calculated by analyzing frequency distributions because the observed dispersion was clearly non-Fisherian. Furthermore, none of the above-mentioned results are constrained by field tests to help date the timing of the remanence acquisition. These three examples are representative of paleomagnetic results from the Neoproterozoic glacial rocks and reiterate the main conclusion of our paper [2].

The second point we wish to restate is the answer to the question 'how low is low latitude?'. We do not deny here, or in our original paper, that the Late Proterozoic glaciations may have occurred at lower latitudes than their Phanerozoic counterparts. However, these glaciations are not necessarily restricted to equatorial regions as required by the high-obliquity model of Williams et al. [1].

Given the overall poor paleomagnetic results from glaciogenic rocks, what might we use to help us discern the latitudinal distribution of continents during these intervals of glaciation? We attempted [2] to use new paleomagnetic data from rock units that date near the time of the glacial intervals and to combine the results with recent tectonic reconstructions for the Neoproterozoic in an effort to extract some useful information regarding the latitudinal drift history of the continents in question. Overall, these data are compatible with our conclusion that these glaciations occurred at latitudes greater than 25°. Of particular importance are the circumpolar glaciations implied by recent data from Baltica [10] and North America [11] because high-latitude glaciations are prohibited by Williams et als.' [1] contentious model for the Earth's obliquity. For example, the new paleomagnetic data place the Port Askaig tillite of Scotland and the Vendian (~ 620 Ma) tillites of Baltica near the south pole. If we are required to use *only* paleomagnetic results obtained directly from glaciogenic rocks we are faced with a nearly intractable problem in trying to solve for the latitudinal distribution of the Neoproterozoic glacial relicts (with the exception of the virtual geomagnetic pole obtained from the Elatina Formation). At the very most there is *no* compelling evidence to argue for a preponderance of strictly low-latitude glaciations required by the model of Williams et al. [1].

We also wish to reply to two misleading statements in the comment of Williams et al. [1]: Williams et al. [1] imply that we have made a link between our Catoctin results and the ca. 750 Ma glacial relicts in Virginia in some effort to correlate these with the Marinoan glaciation. We did not mention the alpine glacial relicts in Virginia for precisely the reasons stated by Williams et al. [1] and therefore the Virginia alpine glacials are irrelevant to *either* argument! Williams et al. [1] make the claim that recent paleomagnetic data from North America indicate 'low' paleolatitudes for North America during the Icebrook glaciation. This is demonstrably wrong as the paper [12] cited in the comment by Williams et al. [1] lists the Ice Brook paleolatitude at 51°S! Secondly, Williams et al. [1] make claims for much finer age control than is reasonable given the dearth of unequivocal fossil evidence and complete lack of radiometric age control on the Neoproterozoic glaciogenic rocks. Therefore, to distinguish between glacial deposits formed during a period of a purported high obliquity and those deposited after the Earth's recovery from a high obliquity is, at best, a rather tenuous differentiation. Thus, not only is the Neoproterozoic climate paradox not preserved, it has never been clearly established by a preponderance of high-quality paleomagnetic data. [***MK***]

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