Integrated global correlation of the Late Neoproterozoic: Exploring the glacial roots of the Metazoa

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Interpretation of the Late Neoproterozoic glacial record has ranged from global synchronous glaciation to local rift-related glaciation, and debate continues in earnest. One of the main reasons that such disparate interpretations are still considered is the lack of precision in worldwide Neoproterozoic correlation, principally due to the lack of Precambrian biostratigraphy. Greater reliance must therefore be placed on chemostratigraphy, lithostratigraphy and, perhaps most importantly, precise geochronology. Reliable radiometric dates for the Neoproterozoic have been rare, but are increasing in abundance as both the Snowball Earth hypothesis and the placement of the GSSP for the Ediacaran system at the base of the Nuccaleena Formation (cap dolostone of the Elatina Formation) in South Australia have focused attention on the Cryogenian & Ediacaran.
Here we present a new correlation of the Late Neoproterozoic record, based principally on a compilation of all available precise radiometric dates for the interval, and backed up by lithostratigraphic (cap carbonates and iron formations) and chemostratigraphic (carbon and strontium isotopes) evidence where available. The situation is more complex than the two or three simple glaciations envisaged by previous authors.
Most glaciogenic strata of Ediacaran age have been previously correlated with the Gaskiers glaciation, well dated at c. 580 Ma in Newfoundland, however occurrence of diamictites in Germany significantly younger than the Gaskiers, and the apparent presence of two Ediacaran diamictites in Scotland, indicates that simple attribution of all Ediacaran diamictites to the Gaskiers phase may prove insupportable. However, the Moelv & Mortenses diamictites of Norway, and the Egan of Australia, do appear to be equivalent in age to the Gaskiers, and it appears that the unconformity separating the Upper Sequence and the Miaohe Member of the Doushantuo Formation is also of this age. No non-actualistic conditions are apparent at this time.
The best constrained glaciation of the Neoproterozoic occurs at the end of the Cryogenian Period by definition. Previously glaciogenic strata of this age were referred to as "Marinoan", however this is an Australian stratigraphic term encompassing the glaciogenic strata and the entire Ediacaran System and is therefore not appropriate. We suggest the name 'Elatina', after the diamictite on which the Ediacaran GSSP rests. Equivalent strata occur in South China (Nantuo), Tarim Block (Tereeken), Namibia (Ghaub), DR Congo (Petit Conglomérat), Oman (Fiq), North Africa (Fersiga, Jbeliat), Brazil (Puga), Norway (Smalfjorden), North America (Stelfox, Mt. Vreeland, Kingston Peak), Greenland (Storeelv), and Svalbard (Wilsonbreen). Radiometric constraints place this glaciation as beginning after ~660 Ma, and terminating synchronously worldwide at 635 Ma. These dates also confirm the utility in global chronostratigraphy of the Nuccaleena-style "cap dolostone", the pale pinkish to buff coloured thin (3 – 30m) laterally extensive unit of microcrystalline dolomite which is observed to overlie many glaciogenic diamictites of Neoproterozoic age.
Copious evidence in many locations worldwide also exists for glaciation bracketed between 715 - ~680 Ma, which has commonly been referred to glaciogenic strata (Sturt/Appila/Areyonga diamictites) of the local Sturtian Series in South Australia. Other diamictites which fall into this bracket include the Chuos of Namibia, the Rapitan and equivalents of W. North America (including the Pocatello & Edwardsburg), the Konnarock & Mechum River of E. North America, the Tiesiao of S. China, the Tsaagan Oloom of Mongolia, the Ghubrah of Oman, the Grand Conglomérat of DR Congo, and the Goldie of Antarctica. Many of these are associated with iron formations, and they are also in several cases overlain by distinctive postglacial carbonates, although in no cases is a "cap dolostone" identical to the Nuccaleena present.
Finally, a growing body of evidence supports glaciation prior to the Sturtian. Included in this is the Kaigas of the Gareip Belt, the Jequitai of Brazil, the Chang'an of South China and the Bayisi of

North China. Several diamictites in Africa are very poorly constrained but also may be older than the Chuos, including diamictites in Zaire previously linked to the DR Congo Grand Conglomérat. Low $\delta^{18}O$ zircons dated to ~760 Ma from South China also support pre-Sturtian cold climate. No evidence exists, however, to suggest any non-actualistic conditions.

Missing from the above correlation is palaeontological information, to avoid circular arguments. Many authors have previously speculated about the role of the Neoproterozoic glaciations in early animal evolution. This compilation, which also includes a compilation of Neoproterozoic biostratigraphic data, now demonstrates unequivocally that the glaciations and rapid evolutionary change in the Neoproterozoic were inextricably linked.

Acritarchs, organic walled microfossils of disputed affinity, are predominantly simple & long ranged prior to the glacial interval, however in the aftermath of the Elatina glaciation, short-ranged, large acanthomorphic (process-bearing) taxa appear; these become extinct again at c. 580 Ma coincident with the Gaskiers. Uncertainty has abounded here in the last few years due to appearance of many of these after the Acraman Impact in Australia, previously estimated at 580 Ma, however this estimate was directly associated with an estimate of 600 Ma for the end of the Elatina glaciation, which is of course too young by some 35 Myr. The estimate for the age of the Acraman is thus likely to also be a significant underestimation.

Simple discoidal "Ediacaran-type" fossils appear for the first time below Stelfox (Elatina equivalent) glacial strata in N. America, and the Fersiga diamictite in N. Africa; these may represent poriferan-grade organisms. No Ediacaran-type fossils are present between Elatina & Gaskiers glacial strata, and complex Ediacaran fossils first appear shortly above the Gaskiers diamictite in Newfoundland, & the equivalent Mortensnes in Norway. Similar relationships are observed elsewhere.

Molecular clock dates are now coming in line with the fossil record. The latest dates (Peterson & Butterfield 2005, PNAS) suggest the origin of the Porifera at 664 Ma, the Porifera/Cnidaria divergence at 634 Ma, the first bilaterians at 604 Ma, and the protostome/deuterostome split at 579 Ma. The coincidence of these dates with the microfossil record has already been remarked on; the coincidence with the precise geochronological constraints on the Neoproterozoic glaciations is nothing short of remarkable. This evidence is summarised in Figure 1. This strongly suggests that the origin of the major metazoan clades was closely linked to at least the Sturtian, Elatina and Gaskiers glaciations. This may have been due to glaciation-induced mass extinctions, with major post-extinction diversification; cold climate may also have driven evolutionary radiation of animals in particular by increasing the oxygen content of seawater. Alternatively, both glaciations and evolution were controlled by the same external factors e.g. atmospheric conditions.

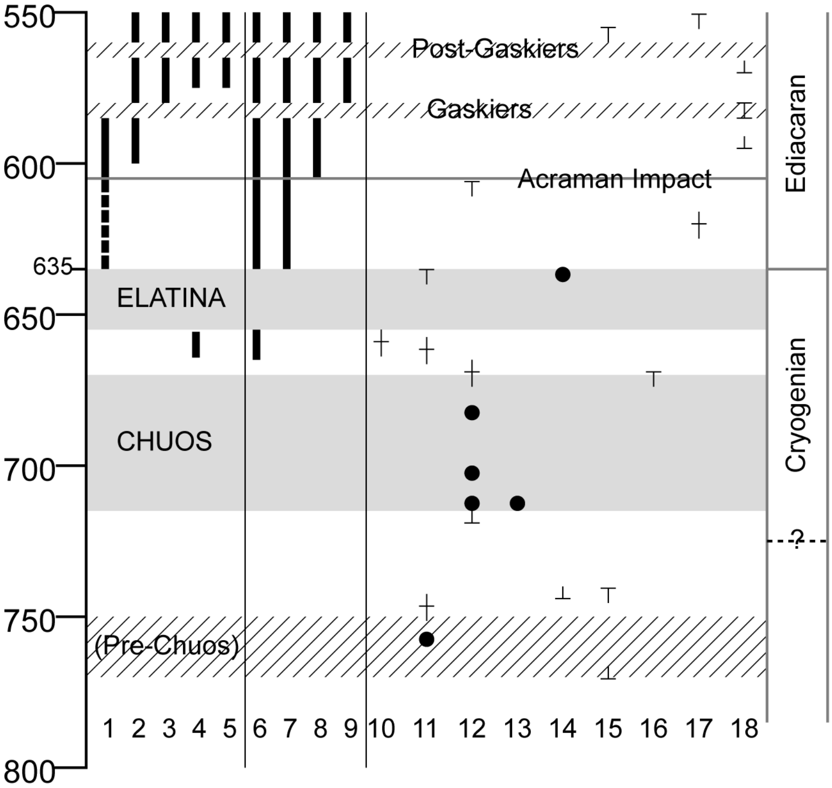

Figure 1. **Glacial Origin of life**.
1-5 Palaeontological evidence,
1. DPM 2. Doushantuo embryos 3. Miaohe Biota 4. Ediacaran-type discs 5. Complex "Ediacarans"

6-9 Molecular clock data (Peterson & Butterfield 2005 PNAS),
6. Porifera 7. Cnidaria 8. Bilateria 9. Deuterostoma

10-18 Radiometric dates for
10. Australia 11. China 12. Laurentia 13. Arabia 14. Congo 15. Gareip 16. Antarctica 17. Baltica 18. Avalonia/Cadomia.
⊥ Max.constraint ⊤ Min. constraint
● Syn-glacial