Age constraints on Precambrian glaciations and the subdivision of Neoproterozoic time

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Abstract

A review of age constraints on the Neoproterozoic glaciations suggests that at least four distinct glacial events can be recognised, three of which appear to be global. These are (in order from oldest to youngest) the Kaigas (poorly constrained to between 770 and 735 Ma), Sturtian (well constrained to c. 715 - 680 Ma), Marinoan (well constrained to 660 - c. 635 Ma), and Gaskiers (extremely well constrained to c. 585 - c. 582 Ma). Excellent correspondence of some U-Pb dates suggests that these glaciations may be of practical use in global chronostratigraphy, a principle previously recognised by the IUGS Terminal Neoproterozoic Subcommission in the placement of the GSSP for the base of the Ediacaran System at the base of a Marinoan "cap carbonate". It is here suggested that the newly constituted IUGS Ediacaran Subcommission follow this principle by searching for appropriate sites and horizons to place GSSPs (a) for the base of the Upper Series of the Ediacaran System (for which the name Vendian is suggested) immediately above a "Gaskiers" diamictite, (b) for the base of the Upper Series of the Cryogenian System at the base of a "Sturtian" diamictite, and (c) for the base of the Cryogenian System at a level between the top of the "Kaigas" diamictites, and the base of the "Sturtian" diamictites. This would confine the four glaciations and the subsequent rise of metazoans to a separate Series each, and combines the two greatest glaciations in Earth history, the Sturtian and Marinoan glaciations, as the Cryogenian System. While there may be reasons to consider other names, the widespread use of the names "Sturtian" and "Marinoan" in the literature suggests the Subcommission should consider these names for the Lower and Upper Series of the Cryogenian respectively.

1. Introduction

The ubiquitous occurrence of diamictites comparable to Quaternary tillites in Latest Precambrian strata worldwide has long been noted, and the idea that this time witnessed the greatest glaciations in the history of our planet has been around close on 50 years (see review in [1]). In recent times, these glaciations have been the subject of considerable controversy, as palaeomagnetic data suggested glaciers extended to sea level in equatorial regions [2]. This data, and carbon isotope data, led to the famous Snowball Earth theory, which proposed that the entire world was frozen over by ice, until a runaway greenhouse effect produced by CO_2 buildup in the atmosphere caused rapid melting of the ice sheets, followed by global precipitation of carbonate in the world's oceans, producing the carbonate "caps" observed to top diamictites in many locations [3]. Subsequent modifications of the theory [4], and alternative proposals for cap carbonate genesis [5, 6] have failed to decrease the controversy, however the global extent of the glaciations has been generally accepted (although dissenters remain [1]).

Attention on the Neoproterozoic glaciations has further been focused by the use of their supposed global nature by the IUGS Terminal Neoproterozoic Subcommission, who placed the GSSP for the base of the newly defined Ediacaran System at the base of a "cap carbonate" overlying a diamictite of "Marinoan" age in Australia [7]. Use of this level to define a global chronostratigraphic boundary has subsequently been borne out by the close correspondence of dates (see below) for this level from China and Namibia, although correlations of this type are often uncertain: indeed, some of the correlations used to constrain the age of the GSSP in the original proposal [8] have subsequently proved incorrect! The purpose of this paper is to review the current age constraints on the Neoproterozoic diamictites; to ascertain whether or not any other diamictite horizons can be of use to the IUGS Ediacaran Subcommission in the future subdivision of Neoproterozoic time; and to propose levels for new GSSPs based on this.

2. Correlation of diamictites

2.1 Laurentia

If worldwide correlation of diamictites is possible, then correlation of diamictites across palaeocontinents should be reasonably straightforward. On this basis, lithostratigraphic correlations across Laurentia have been attempted (Fig. 1). It appears that strata close to the present-day western coast of the United States of

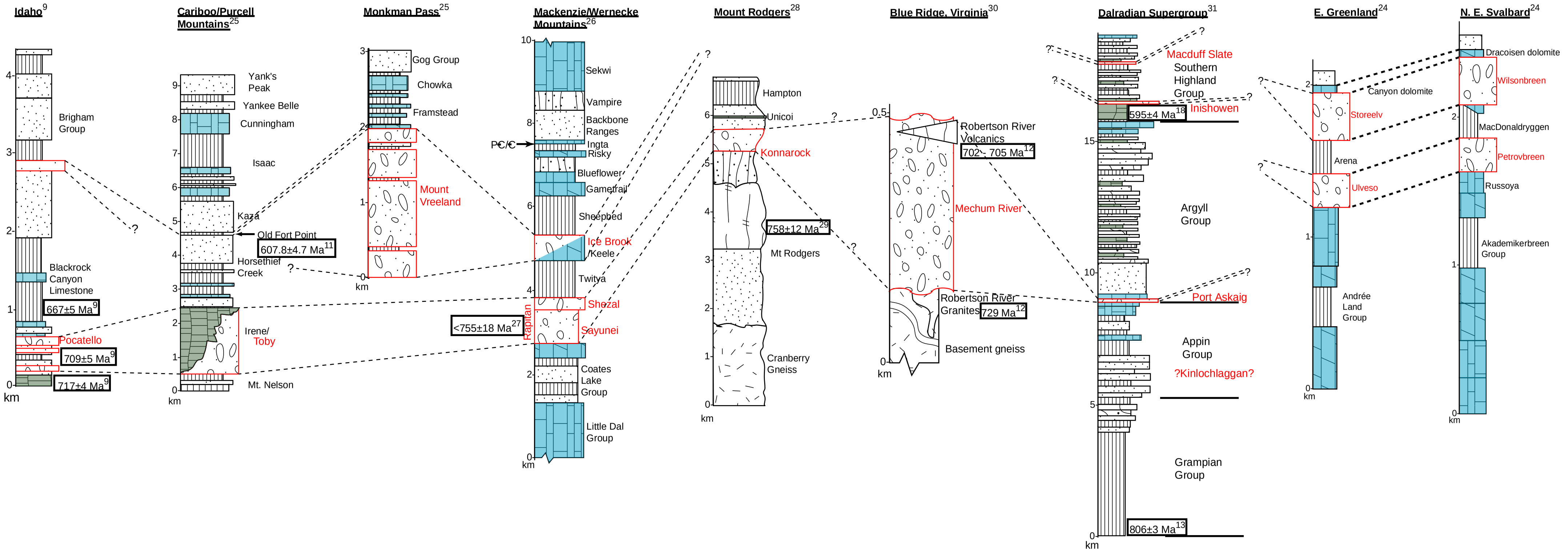


Figure 1: Lithostratigraphic correlation of Neoproterozoic stratigraphic sections across Laurentia.

America and Canada (the Windemere Supergroup and equivalent strata) record two glaciation events, correlatives of the Rapitan and Ice Brook diamictites of the Mackenzie Mountains. Consideration of radiometric dates for these constrains the older event to have begun after 717±4 Ma [9], be ongoing at 709±5 Ma [9] and 684±4 Ma [10], and be over by 667±2 Ma [9]. The younger event must have begun after the 667±5 Ma date, and must have been over by 607±4 Ma [11].

The Appalachian region of the United States of America appears to record only one glaciation event, which appears to correlate to the older Rapitan glaciation of the Windemere Supergroup; radiometric dates indicate commencement of glaciation sometime after 730 Ma, and be still ongoing at 702 Ma [12]. This matches the dates from the Windemere Supergroup perfectly. However, the Dalradian Supergroup of Ireland and Scotland, supposedly equivalent to the Appalachians, contains at least three and possibly four diamictites. Correlation of these with the rest of Laurentia is problematic. The oldest of the Dalradian diamictites, the Port Askaig Tillite, is constrained only between 809±3 Ma [13] and 601±4 Ma [14], and thus could represent the equivalent of either of the two western North American diamictites, however chemostratigraphy and the thickness of strata between the tillite and the 601 Ma date have been used to infer an older age [15], which is accepted here. The Inishowen diamictite [16], consisting of multiple deep marine dropstone horizons [17], lies not far above volcanics dated at 595±4 Ma [16, 18], and thus both it and the overlying Macduff Tillite [19] curiously record glaciations not observed elsewhere in Laurentia. However, the Macduff Tillite is of disputed age [20], and may postdate the Ediacaran. Finally, the Kinlochlaggan Boulder Bed [21] is of disputed stratigraphic position, and limited exposure, and has been suggested by some authors to be an equivalent to the Port Askaig Tillite [22]. However others prefer an age much older than the Port Askaig Tillite [23]. While it's stratigraphic position within the Dalradian is disputed, correlation with other Neoproterozoic sections is at best speculative.

Correlation between Greenland, Svalbard and Spitsbergen appears to be straightforward [24], however correlation of these units to the rest of Laurentia is problematic. These strata contain two distinct diamictite horizons, however it is uncertain whether these should be correlated to the two Windemere diamictites, or whether one of them represents one of the younger glaciations observed in the Dalradian Supergroup.

2.2 Avalonia and peri-Gondwana terranes

Diamicites are also observed in the palaeocontinent of Avalonia. The best known of these is the Gaskiers diamictite of Newfoundland, the age of which is extremely well constrained. Deposition of the diamictite began after 583.7±0.5 Ma, was continuing at 582.4±0.4 Ma, and had ceased by 582.1±0.4 Ma (S. Bowring, pers. comm. June 2005). Exposures in Newfoundland also indicate how much care is needed when interpreting radiometric dates, as strata below the Gaskiers diamictite are consistent with eustatic sealevel fall, consistent with the idea that the glaciation was ongoing elsewhere prior to the deposition of diamictites in Newfoundland.

Other Avalonian locations are consistent with evidence from Newfoundland, with potentially glaciogenic strata in Boston (Squantum tillite, younger than 596±2 Ma [32]) and northern France (Granville Formation of the Brioverian Supergroup, younger than 584±4 Ma [33]) of seemingly similar age to the Gaskiers diamictite. It should be noted that there is no proof of glacial influence on the Granville Formation, however absence of evidence is not evidence of absence, and a glacial influence must still be considered possible.

Strata in Saxo-Thuringia may also be of potentially equivalent age, with detrital zircons younger than the upper Windemere glaciation having been recovered from the diamictite [34]. These cluster around a 570 Ma age, however the ages are spread out and the diamictites could be correlatives of the Gaskiers.

It is notable that the age of these diamictites is entirely consistent with a correlation between the Avalonian diamictites, and the Inishowen diamictite of the Dalradian Supergroup of Irish Laurentia (younger than 595±4 Ma). Since the tillite in Newfoundland is the best known and studied of these, the name “Gaskiers” will subsequently be used to refer to this glaciation.

2.3 South China

In the last year, several different groups have dated tuff beds in south China, providing high resolution control on the age of parts of the succession there. A high precision date of 635.23±0.48 Ma on a tuff bed within the cap carbonate overlying the Nantuo diamictite [35] provides a tight control on the termination of this glaciation, while a date of 663±4 Ma from the underlying Datangpo Formation [36] provides a maximum age. This is consistent with correlation to the younger glaciation in Western North America. The 663±4 Ma date also provides a maximum age constraint on the termination of the older Tiesiao glaciation; the northern Guizhou section also appears to record an even older Changan glaciation. A date of 761±8 Ma from the underlying Liantuo Formation [37] provides a maximum age constraint on both older glaciations. Here, correlation with Laurentia is again uncertain, as there appears to be two older glaciations here for one in Laurentia. One possible interpretation is that the Tiesiao diamictite is equivalent to the older Western North American diamictite, and that the Changan diamictite records a glaciation not observed in Laurentia, however other interpretations are possible.

2.4 Northern China

Three diamictites are also observed in the Quruqtagh Group in northern China. These were correlated to other diamictites worldwide based on lithostratigraphy of the cap carbonates, and supported by biostratigraphy in the form of vendotaenid fossils [38]. The potentially (but not unequivocally demonstrably) glaciogenic Bayisi Formation has thus been correlated with the older Windemere glaciation; the younger and demonstrably glaciogenic Tereeken & Altungol Formations have been correlated with the younger Windemere glaciation. The demonstrably glaciogenic and younger again Hankalchough Formation would then correlate with the Gaskiers glaciation at c. 585-2 Ma. The sole radiometric age constraint on this group is a date of 755±15 Ma on volcanics underlying the Bayisi Formation [39], providing only a maximum age constraint for the whole group.

2.5 Southern Africa

The Otavi Group in Namibia records two glaciations on the Congo craton. The older Chuos diamictite overlies volcanics dated at 746±2 Ma [40], while an ash bed within the deglaciation phase of the younger Ghaub diamictite has been dated at 635.5±1.2 Ma [41]. This allows correlation of the Chuos with the older Windemere diamictite, and of the Ghaub with the younger. It is noted that the 635 Ma date on the Ghaub tillite exactly matches that from South China, strongly supporting global synchroneity of Neoproterozoic glaciations.

Two glaciations are also represented in Southern Namibia, on the Kalahari craton. However here, correlation is different. Granites underlying the sequence have been dated at 780±10 Ma [42], providing a maximum age for the older Kaigas glaciation, while rhyolites dated at 741±6 Ma [43] provide a minimum age for the Kaigas diamictite and a maximum age for the younger Numees glaciation. While the Numees may thus correlate with the older Windemere glaciation, the Kaigas appears to have no equivalent represented in Laurentia (apart perhaps from the Kinlochlaggan Boulder bed if its stratigraphic position below the Port Askaig Tillite is confirmed), although it may correlate with the Changan glaciation of South China. This provides evidence of a fourth discrete Neoproterozoic glacial event.

2.6 Oman

Two glaciations are represented in Oman, by the older Gubrah and younger Fiq diamictites. An ash bed within the older diamictite has been dated at 711.8±1.6 Ma [44], in precise agreement with dates from Laurentia indicating glaciation ongoing at this time. The Fiq glaciation [45] probably correlates with the younger Windemere glaciation, although it has not, as yet, been radiometrically dated.

2.7 Ethiopia

The Negash diamictite of Ethiopia overlies granites dated at c. 750 Ma [46], providing a maximum age, and is intruded by granites dated at 613 Ma [47]. The younger granites also postdate an early deformation event, indicating a long time between deposition and intrusion. This is consistent with a correlation to the older Windemere diamictite.

2.8 Brazil

The glaciogenic Jequitai diamictite on the Sao Francisco Craton is overlain by volcanics dated at 740±22 Ma [48], which precludes the possibility of correlation with the older Windemere diamictite. This may be an equivalent of the Namibian Kaigas diamictite.

The Puga diamictite on the Amazonia craton overlies volcanics dated at 623±15 Ma [49]. This precludes correlation with the younger Windemere diamictite, but is consistent with referral to the Gaskiers glaciation.

2.9 Baltica

Detrital zircons from sediments significantly underlying the Moelv tillite in Baltica, the younger of two diamictites previously both referred to the “Varanger” glaciation, have been dated at 620±14 Ma [50]. This is consistent with correlation between the Moelv Tillite and the Gaskiers Tillite. The Moelv tillite is locally correlated with the Mortenses diamictite on the Varanger Peninsula of Norway. The underlying Smalfjorden diamictite would then probably correlate with the younger Windemere diamictite.

2.10 Australia
Several diamictites are represented in Australia, however a lack of radiometric dates hampers correlation efforts. The Sturtian tillite is generally thought, based on cap carbonate lithostratigraphy and chemostratigraphy, to correlate to the Rapitan glaciation of Canada and the Chuos glaciation of Namibia. The younger Marinoan glaciation is similarly correlated with the Namibian Ghaub tillite, and the Chinese Nantuo tillite. The GSSP for the Ediacaran System is placed at the base of the cap carbonate overlying the Elatina Formation, a Marinoan diamictite [7]. Based on stromatolite biostratigraphy, a third glaciation, the Egan tillite, was identified in Northern Australia to be younger than the Marinoan tillite [51]. This may correlate to the Gaskiers glaciation. There are also reports of South Australian diamictites younger than the Marinoan tillite [52], which would be similarly correlated.

The Cottons Breccia of Kings Island, Tasmania, previously correlated with the Marinoan glaciation [53], is intruded by sills dated at 575±3 Ma [54]. This has also been correlated with the Croles Hill Diamictite of Tasmania, which is underlain by rhyodacite dated at 582±4Ma [54]. This presents a problem, as here we have supposed-Marinoan equivalent diamictite constrained to c. 580 Ma, identical within error to the Gaskiers glaciation. Given the robust nature of the correlation of the Marinoan tillite with well dated sections in Namibia and China, it is more likely that the Croles Hill Diamictite and Cottons Breccia are not equivalent to the Marinoan tillite, but instead provide further evidence of widespread glaciation at c. 585-2 Ma.

3 Summary of correlations
A summary of age constraints and correlations is presented in Figure 2. Four distinct Neoproterozoic glacial episodes have been recognised:

3.1 Sturtian
The Sturtian glaciation of Australia is correlated with the Rapitan, Toby, Misinchinka, Edwardsburg, Pocatello, Port Askaig, Mechum River, and Konnarock diamictites of Laurentia. The Chuos and Numees diamictites of Namibia, the Gubrah diamictite of Oman, the Tiesiao and Bayisi diamictites of China, and probably the Negash diamictite of Ethiopia also correlate with the Sturtian glaciation. Dates from Idaho indicate that glaciation began after 717±3 Ma (clast) and was ongoing at 709±4 Ma, while dates from Oman indicate glaciation was ongoing at 712±2 Ma. The start of the glaciation is thus constrained to c. 715 Ma. Further data from Idaho indicates that the glaciation was ongoing at 684±4 Ma, but had finished by 667±2 Ma, which is supported by 663±4 Ma dates from China. The Sturtian glaciation thus ended sometime around 680 Ma.

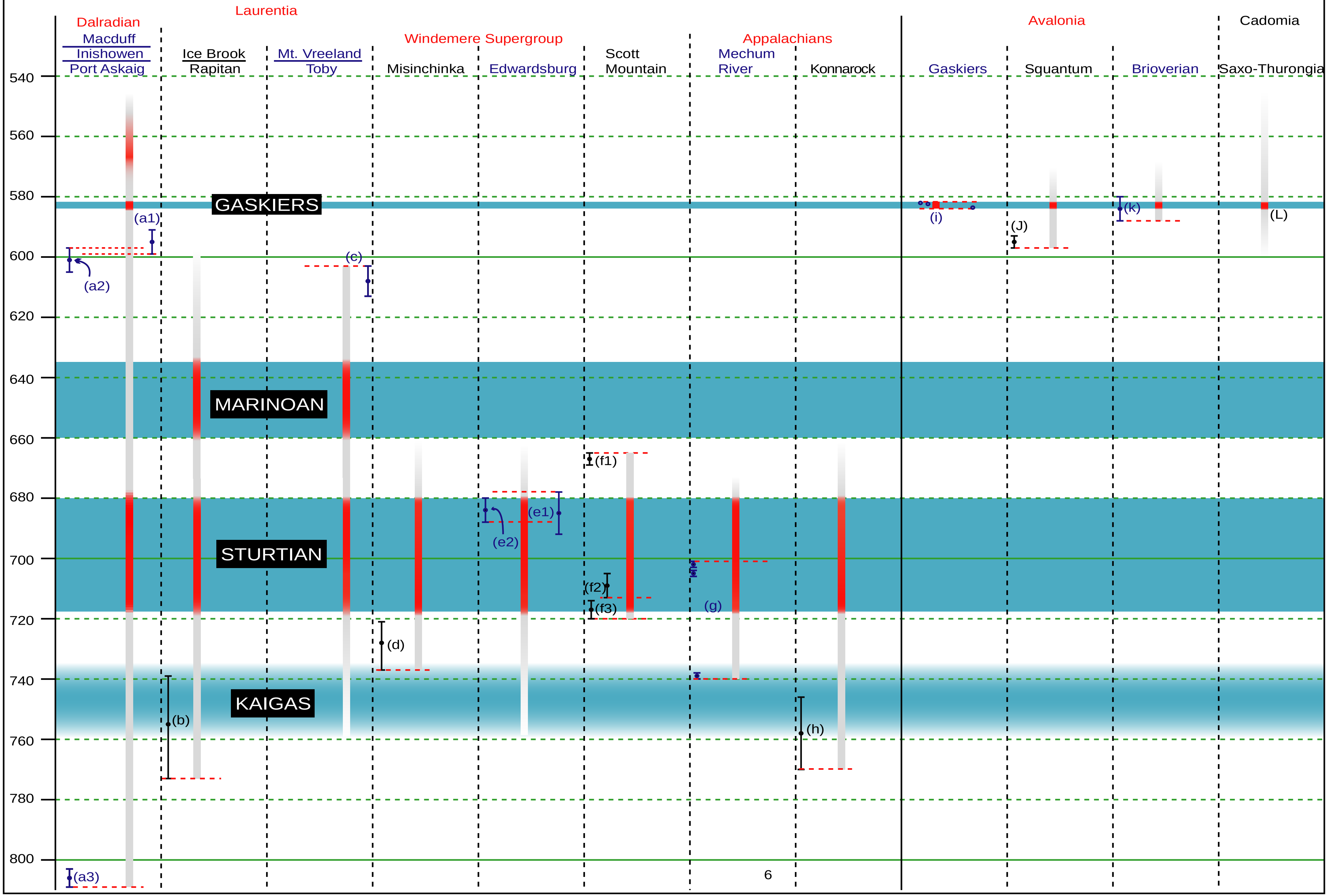
3.2 Marinoan
The Marinoan glaciation is correlated with the younger Windemere glaciation, represented by the Ice Brook and Mt. Vreeland diamictites. It is also represented by the Ghaub diamictite in Namibia, and the Nantuo and Altungol-Tereeken diamictites of China. The older “Varanger” glaciation of Baltica probably also represents the Marinoan. A maximum age constraint is provided by 663±4 Ma dates from preglacial strata in China, while the end of the glaciation is precisely dated at 635.23±0.57 Ma in China.

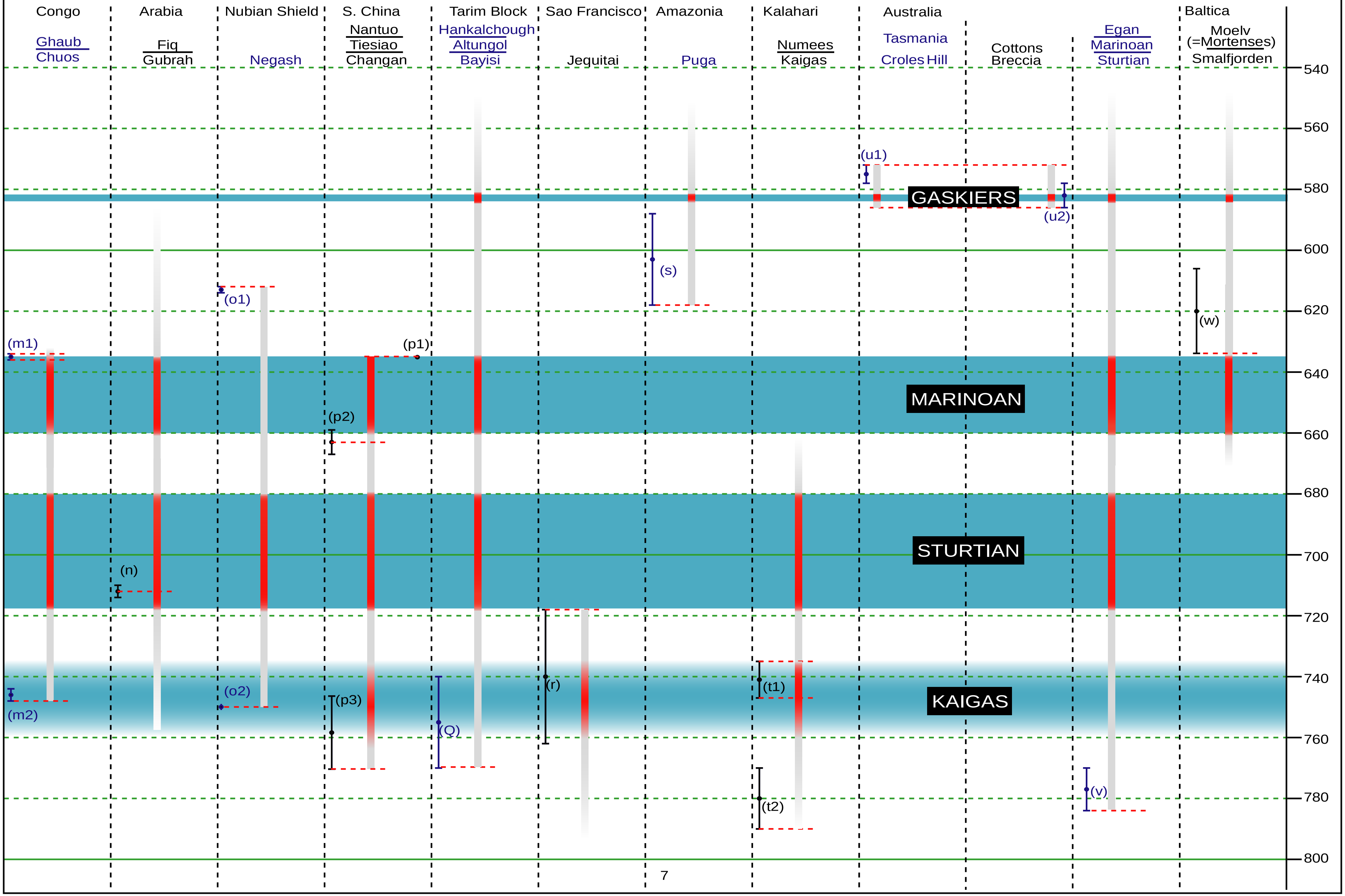
3.3 Gaskiers
The Gaskiers glaciation is also represented by the Squantum tillite, the Saxo-Thuringian tillites, the Moelv and Mortenses tillites of Norway, the Egan diamictite of Australia, the Croles Hill diamictite and Cottons Breccia of Tasmania, the Puga diamictite of Brazil, the Irish Inishowen diamictite and possibly the Brioverian diamictites of the Granville Formation. As noted above, the Gaskiers glaciation may have been ongoing prior to the 584 Ma older date from Newfoundland, however the end of the glaciation is precisely constrained at 582 Ma, and dates from Australia and elsewhere agree with those from Newfoundland.

3.4 Kaigas
Finally, the Kaigas glaciation of Namibia also appears to be represented by the Jequitai diamictite of Brazil, and possibly the Changan glaciation of South China. This is poorly dated, with constraints from Namibia placing it between c780 and c735 Ma, and dates in China providing a maximum age of c. 770 Ma. The lack of correlatives worldwide suggest this glaciation may not have been as severe as the Marinoan or Sturtian.

4 Use in Global Chronostratigraphy
The global extent of the Sturtian, Marinoan and Gaskiers diamictites having been proposed, I believe that these can be used for global chronostratigraphic purposes. The Marinoan, of course, has already been used, and it is here proposed to use the Sturtian and Gaskiers glaciations similarly.

Figure 2: Correlation of Neoproterozoic Diamictites




Congo
Ghaub
Chuos
Arabia
Fiq
Gubrah
Nubian Shield
Negash
S. China
Nantuo
Tiesiao
Changan
Tarim Block
Hankalchough
Altungol
Bayisi
Sao Francisco
Jequitai
Amazonia
Puga
Kalahari
Numees
Kaigas
Australia
Tasmania
Croles Hill
Cottons
Breccia
Egan
Marinoan
Sturtian
Baltica
Moelv
(=Mortenses)
Smalfjorden
GASKIERS
MARINOAN
STURTIAN
KAIGAS
(m1)
(m2)
(n)
(o1)
(o2)
(p1)
(p2)
(p3)
(Q)
(r)
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(t1)
(t2)
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(u2)
(v)
(w)
540
560
580
600
620
640
660
680
700
720
740
760
780
800

Table 1: Age Constraints on Neoproterozoic Diamictites used in Figure 2

a1	Tayvallich keratophyre	U-Pb	595±4 Ma	18
a2	Tayvallich tuffs	U-Pb	601±3 Ma	14
a3	Intruding pegmatite	U-Pb	806±3 Ma	13
b	Granite clast	U-Pb	755±18 Ma	27
c	Old Fort Point black shale	Re-Os	607.8±4.7 Ma	11
d	Basement gneiss		728+9/-7 Ma	quoted in 2
e1	Interbedded volcanics	U-Pb	684±4 Ma	10
e2	Interbedded volcanics	U-Pb	685±7 Ma	10
f1	Overlying tuff	U-Pb	667±2 Ma	9
f2	Interbedded tuff	U-Pb	709±4 Ma	9
f3	Clast of basement recovered from diamictite	U-Pb	717±3 Ma	9
g	Basement granite	U-Pb	729 Ma	quoted in 12
	Interbedded rhyolites	U-Pb	702 & 705Ma	quoted in 13
h	Underlying volcanics	U-Pb	758±12 Ma	29
i	Tuff above diamictite	U-Pb	582.1±0.4	Bowring, pers. comm.
	Tuff within diamictite	U-Pb	582.4±0.4	Bowring, pers. comm.
	Tuff below diamictite	U-Pb	583.7±0.5	Bowring, pers. comm.
J	Tuff clast from diamictite	U-Pb	596±2 Ma	32
k	Cuts intrusion aureole	U-Pb	584±4 Ma	33
L	Many detrital zircons	U-Pb	c.570 Ma, ±c.30Ma	34
m1	Tuff in deglaciation phase	U-Pb	635.5±1.2 Ma	41
m2	Underlying volcanics	U-Pb	746±2 Ma	40
n	Interbedded tuff	U-Pb	711.8±1.6 Ma	44
o1	Younger granite	U-Pb	613.4±0.9 Ma	47
o2	Older granite	U-Pb	c. 750 Ma	quoted in 46
p1	Tuff within cap carbonate	U-Pb	635.23±0.57 Ma	35
p2	Tuff in Datangpo Formation	U-Pb	663±4 Ma	36
p3	Underlying volcanics	U-Pb	761±8 Ma	37
q	Vendotaenid fossils biostratigraphy and cap carbonate lithostratigraphy			38
q1	Underlying volcanics	U-Pb	755±15 Ma	39
r	Overlying volcanics	U-Pb	740±22 Ma	48
s	Underlying volcanics	U-Pb	623±15 Ma	49
t1	Rhyolite between diamictites	U-Pb	741±6 Ma	43
t2	Underlying granite	U-Pb	780±10 Ma	42
u1	Intruding sills	U-Pb	575±3 Ma	27
u2	Underlying rhyodacite	U-Pb	582±4 Ma	27
v	Stromatolite biostratigraphy and cap carbonate lithostratigraphy			51
v1	Unconformably underlying volcanics	U-Pb	777±7 Ma	quoted in 2
w	Detrital zircon from underlying formation	U-Pb	620±14 Ma	42

Figure 2: Correlation of Neoproterozoic Diamictites
Age points are shown with error bars where possible. Grey bars show the possible range of stratigraphic ages of the diamictites, faded to white where there is no significant constraints. Red bars indicate precisely known ages (indicated by age points) or ages as interpreted herein. References beside ages points refer to Table 1. Horizontal blue bars indicate the age ranges of the Neoproterozoic glaciations, as proposed herein. Names of diamictites are given at the top of each column in stratigraphic order.

4.1 Gaskiers

Many other researchers have shown the first-order influence the Gaskiers glaciation had on Neoproterozoic evolution. In Newfoundland, the first Ediacaran fossils [55] appear within 4 Myr of the end of the Gaskiers glaciation, and there is similar relationships with evolution in China [35]. The end of the Gaskiers glaciation, marking a pivotal point in the evolution of life, is an ideal horizon for a first order subdivision of the Ediacaran System. It is therefore proposed to place the GSSP for the Upper Series of the Ediacaran System at a level marking the termination of the Gaskiers glaciation. At least two Gaskiers diamictites (the type Gaskiers at Harbour Main in Newfoundland [56], and the Hankalchough Diamictite of North China [38]) have cap carbonates. That of the type Gaskiers is extremely discontinuous, and in places apparently not in situ (personal observations). It is therefore not suitable as a GSSP location. The base of the cap carbonate overlying the Hankalchough Formation may provide one possibility. However, the Subcommission way also wish to consider locations lacking a cap carbonate.

It is proposed that the name Vendian, having long been used in the literature to refer to the latest Neoproterozoic time dominated by the Ediacaran-type soft bodied fossils, would be an eminently suitable name for the Upper Series of the Ediacaran.

4.2 The Lower Cryogenian Boundary

Given the unequivocal nature of the Sturtian and Marinoan glaciations as the two greatest glaciations in the Neoproterozoic, if not the entire history of our planet, their combination as Cryogenian System is a natural arrangement. Further, a precedent has been set with the exclusion of the Gaskiers glaciation from the Cryogenian System, that this system need not include all Neoproterozoic glaciations. Given the importance in earth history of the Sturtian and Marinoan glaciations, and the uncertain nature of the glaciations older than Sturtian, it is proposed to place the GSSP for the base of the Cryogenian System at a level below the base of the Sturtian diamictites, but above the top of the older diamictites. This would confine only the two great glaciations to the Cryogenian System.

4.3 Sturtian

The termination of the Sturtian glaciation marks the end of the first great glaciation of the Neoproterozoic, and is a natural point at which to place a global chronostratigraphic boundary. Further, given the proposal to combine Sturtian and Marinoan glaciations as the Cryogenian, it follows that the termination of the Sturtian glaciation is a logical horizon for a first order subdivision of the System.

It is thus proposed to place the GSSP for the base of the Upper Series of the Cryogenian System at the base of a cap carbonate overlying a Sturtian diamictite. The well-studied Chuos glaciation of Namibia may be an ideal location for such a GSSP.

Given the common use in the literature of the terms Marinoan and Sturtian, the Subcommission may with to consider the suitability of these names for the lower and upper Series of the Cryogenian System. This would lead to the apparent paradox of having the Sturtian cap carbonate in the Marinoan Series, and the Marinoan cap carbonate would similarly lie outside the Marinoan Series. It may thus be prudent to consider alternatives, however the common use of the names may outweigh this apparent disadvantage.

The proposed chronostratigraphy for the Neoproterozoic is shown in Fig. 3.

4. Dicussion

A bipartite division of both the Cryogenian and Ediacaran Systems, and placement of the lower Cryogenian boundary above the Kaigas diamictites confines each of the Kaigas, Sturtian, Marinoan and Gaskiers glaciations, and the subsequent appearance of metazoan fossils, to separate Series. This approach is entirely natural, given the importance of each of these events to Earth history. Thanks principally to the work of Sam Bowring and colleagues, several boundaries in this proposed chronostratigraphy are dated far more precisely that most of their Phanerozoic counterparts. Further work should attempt to constrain the initiation of the Marinoan glaciation, and the termination of the Sturtian to constrain the Lower/Upper Cryogenian boundary.

Biostratigraphy may be a useful tool in the Ediacaran, with vendotaenid fossils and stromatolites having been used in correlations reviewed here. These and other fossils may have a useful role to play in further subdivision of the Ediacaran. In particular, the appearance of megascopic bilaterian fossils, and the mineralised fossil *Cloudina* should be considered as potential biostratigraphic tools. The work of Grey on Australian acritarchs [57] is one of the most promising developments in Ediacaran stratigraphy, and attempts should be made to asses the applicability of the Australian zonation to other continents, where possible.

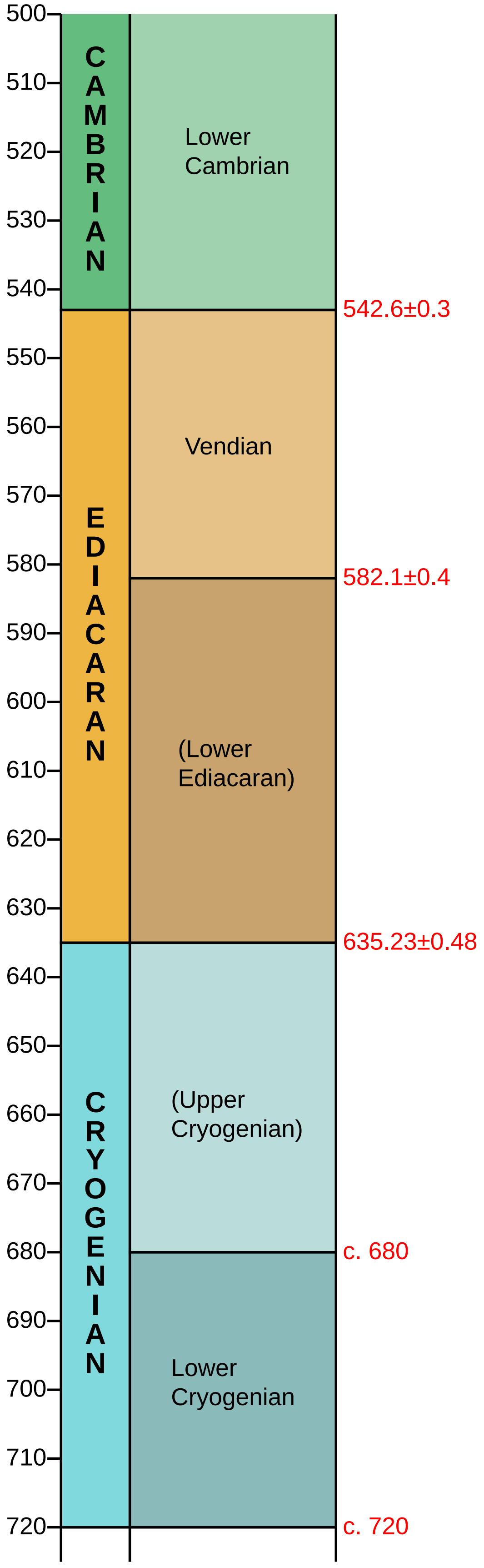

Figure 3: Proposed new timescale for the latter part of the Neoproterozoic. Precise ages (all S. Bowring, pers. comm.) are shown where known, and approximate ages are given where ages are not known, or where no precise level has been suggested for the boundary.

One potential objection which may be raised is the length of the Series of the Ediacaran and Cryogenian: c. 40 Myr for the Lower Cryogenian, c. 45 Myr for the Upper Cryogenian, c. 53 Myr for the Lower Ediacaran, and c. 39 Myr for the Vendian. Compared to Phanerozoic Series, these are quite long: eight Palaeozoic Series, for example, are less than 10 Myr (Wenlock, Ludlow, Pridoli, Upper Mississippian, Lower Middle and Upper Pennsylvanian, and the Lopingian). To put it another way, each of these four Neoproterozoic Series would be longer than the entire Silurian System! However, the same can be said for the Lower and Upper Cretaceous, at 34.1 Myr and 45.9 Myr respectively, which are of similar lengths to the proposed Neoproterozoic Series [58]. The length of these also reflects two important points in Neoproterozoic stratigraphy; the increased difficulty of global correlation at this time, and in the case of the Cryogenian Series, the length of time occupied by the glaciations themselves. The length of the Series should thus not be a significant factor in deciding whether or not to accept this proposal.

Finally, the correlations presented here are based on the inherent assumption of worldwide synchroneity of initiation and termination of Neoproterozoic glaciations. However, the data reviewed here is entirely consistent with this idea, and the almost perfect matching of radiometric dates from far separated localities makes alternative explanations difficult. Further, a precedent has been set with the placing of the Ediacaran GSSP. It is therefore thought that this inherent assumption should not be a significant issue in considering this proposal.

5. Conclusion

A worldwide correlation of the various Neoproterozoic glaciations has been presented, and it has been demonstrated that the available evidence is consistent with four discrete Neoproterozoic glaciations. These are the Kaigas glaciation, poorly constrained to between 770 and 735 Ma; the Sturtian glaciation, constrained to 715 - 680 Ma, the Marinoan glaciation, constrained to 660 - 635 Ma, and the Gaskiers glaciation, well constrained to 585 - 582 Ma. It is proposed to use these glaciations for the purposes of global chronostratigraphy, following the placement of the lower Ediacaran GSSP at the base of a Marinoan cap carbonate, by placing GSSPs: (a) for the Lower Cryogenian boundary below the Sturtian, but above the older diamictites; (b) for the Upper Cryogenian boundary at the base of a cap carbonate overlying a Sturtian diamictite; (c) for the Upper Ediacaran boundary at a level marking the termination of the Gaskiers glaciation. The name Vendian is proposed for the Upper Ediacaran Series: the names Sturtian and Marinoan may be considered as to their suitability for the Lower and Upper Series of the Cryogenian System.

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