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A new rock-based definition for the Cryogenian Period (circa 720 – 635 Ma)

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The Cryogenian Period was first established in 1988 along with other Precambrian eon, era and period-level subdivisions that were defined numerically by Global Standard Stratigraphic Ages (GSSAs). As absolute age constraints have improved, some of these time intervals no longer bracket adequately the geological event(s), for which they were named. For example, the age discrepancy between the basal Cryogenian GSSA at 850 Ma and the onset of widespread glaciation ca. 717 Ma has rendered the 850 Ma boundary obsolete. The International Commission on Stratigraphy has now formally approved the removal of the Cryogenian GSSA from its International Chronostratigraphic Chart and supports its replacement with a rock-based Global Stratotype Section and Point (GSSP). The new Cryogenian GSSP will be placed at a globally correlative level that lies stratigraphically beneath the first appearance of widespread glaciation and is assigned in the interim a ‘calibrated age’ of circa 720 Ma. This new definition for the Tonian/Cryogenian boundary should be used in future publications until a formal Cryogenian GSSP can be ratified. The change marks progress towards establishment of a ‘natural’ (rock-based) scale for Precambrian time.

Evolution of the Cryogenian Period concept

The notion of a widespread glaciation during the late Precambrian was already well advanced (e.g. Kulling, 1934; Lee, 1936; Mawson, 1949) by the time Brian Harland (Harland, 1964a,b) suggested using glacial deposits to define a new addition to the international geological timescale. Harland’s Infracambrian or Varangian System (Fig. 1) began

at the onset of the great “Infracambrian” glaciations and ended at the appearance of recognised Cambrian fossil assemblages. The Subcommission on Pre-Cambrian Stratigraphy did not favour the term ‘Infracambrian’ and suggested its abandonment along with ‘Eocambrian’ and ‘Subcambrian’ in 1969. The term ‘Precambrian’ survived the cull despite calls for its removal (e.g. Cloud and Glaessner, 1982), while ‘Infracambrian’ still persists today without the precise stratigraphic significance given by Harland.

In 1971, Dunn et al. took up the case for a ‘Late Pre-Cambrian’ system beginning at the base of the Sturtian glacial deposits of South Australia. This informal new system attracted widespread support among the geological community and was referred to variously as the “Vendian” (based on the stratigraphy of the East European and Siberian platforms) or the “Sinian” (based on the stratigraphy of South China), covering Neoproterozoic glacial deposits and overlying Precambrian strata (e.g. Harland, 1982). Harland continued to augment his Infracambrian concept, suggesting that the Phanerozoic Eon be preceded by a Sinian Era, comprising Sturtian and Vendian divisions (Harland, 1982; 1990). Since the 1980’s it has been commonplace to subdivide upper Precambrian strata (and time) using glaciogenic deposits and stratigraphic correlation of the successions in which they are found, e.g. Varanger, Elatina (Marinoan), Sturtian, etc.

Despite widespread use of these rock-based terms, purely chronometric subdivisions were introduced in 1988 for the pre-Ediacaran Precambrian (Plumb, 1991). As geochronological data have improved, it has become clear that some of these subdivisions do not accurately cover the aspect of Earth history to which their name refers. In the case of the Cryogenian Period, the chosen interval (850 Ma to c. 635 Ma) is now known to begin about 133 million years before the onset of widespread glaciation (Macdonald et al., 2010), a time span equivalent to the Cambrian, Ordovician, Silurian and early Devonian periods combined. The preceding period, the Tonian Period, was named for the rifting (Tonian = stretching) associated with the break-up of the supercontinent Rodinia (Plumb and James, 1986; Plumb, 1991), which is now believed to have occurred only after 850 Ma (Li et al., 2013), when the Tonian Period had already ended. For such reasons, as well as the inherently imprecise nature of stratigraphic correlation using absolute age constraints (Bleeker, 2004), there has

Direct age constraints on the onset of glaciation

Recent U-Pb and Re-Os data confirm that the Cryogenian glacial interval comprises two main episodes (ca. 717– ca. 662 Ma and ca. 645 – ca. 635 Ma; Rooney et al., 2015). Although possibly older glaciogenic diamictites have been reported (e.g. Kaigas Formation, Frimmel et al. 1996), these rare exceptions have not yet been fully substantiated by stratigraphical, sedimentological or geochronological data. The two most pertinent syn-glacial ages for the older of the two glaciations are the 716.5 (± 0.3) Ma for the Rapitan glacials in NW Canada (Macdonald et al., 2010) and the 714 (± 1) Ma for the Gubrah Formation of Oman (Bowring et al., 2007; see Allen, 2007); note that this latter age has also been cited as 711.8 (± 1.6) Ma (Allen et al., 2002) but has not been published. These ages represent minimum age constraints for the onset of widespread glaciation at low latitudes during the Neoproterozoic, and are consistent with a wealth of maximum age data from strata beneath glaciogenic units (e.g. Rooney et al., 2014; Strauss et al., 2014; Hoffman et al., 1996). Precise U-Pb zircon maximum age constraints for the onset of glaciation are provided by a pre-glacial age of 726 (± 1) Ma for the Leger granite, which predates deposition of the entire Mirbat Group in Oman (Allen, 2007) and 719.5 ± 0.3 Ma for the Kikittak Volcanics, beneath the Hula Hula Diamictite in Arctic Alaska (Cox et al., 2015). Re-Os isochron ages of 727.3 ± 4.9 Ma for the upper Mwashya Formation, beneath the Grand Conglomerat in Zambia and 732.2 ± 4.7 Ma for the Coppercap Formation beneath the Rapitan Group in NW Canada provide complementary maximum age constraints. Together, these

ages are consistent with the pre-glacial age of 717.4 (± 0.2) Ma from NW Canada (Macdonald et al., 2010), which together with the syn-glacial age (716.5 (± 0.3) Ma) from the same region, tightly constrain the onset of low latitude glaciation during the Neoproterozoic at ca. 717 Ma.

Only few successions in the world preserve a transition into Neoproterozoic glaciation because of the erosion caused by eustatic sea-level fall and sub-glacial scouring. The most likely settings where such a transition might be preserved are deeper ones, such as those from parts of South China (northern Guangxi and southern Hunan and Guizhou provinces) where limestones appear within turbiditic mudstones above a volcanic tuff layer dated recently at 715.9 \pm 2.8 Ma and 716.9 \pm 3.4 Ma (Lan et al., 2014). These new age constraints from thick, transitional pre-glacial successions support (1) approximately contemporaneous onset of glaciation on a global scale during the mid-Neoproterozoic; and (2) the lack of any widespread glacial deposits of Neoproterozoic age substantially older than about 717 Ma. The above arguments provide firm support to the proposed interim, calibrated age for the base of the Cryogenian System of ca. 720 Ma.

Stratigraphic correlation of the Tonian-Cryogenian transition

Chemostratigraphy is currently the method of choice for correlating pre-glacial Neoproterozoic strata. Pre-glacial carbonate platforms (Fig. 2) commonly exhibit an extreme negative $\delta^{13}\text{C}$ excursion (referred to as the Islay anomaly). It has been proposed

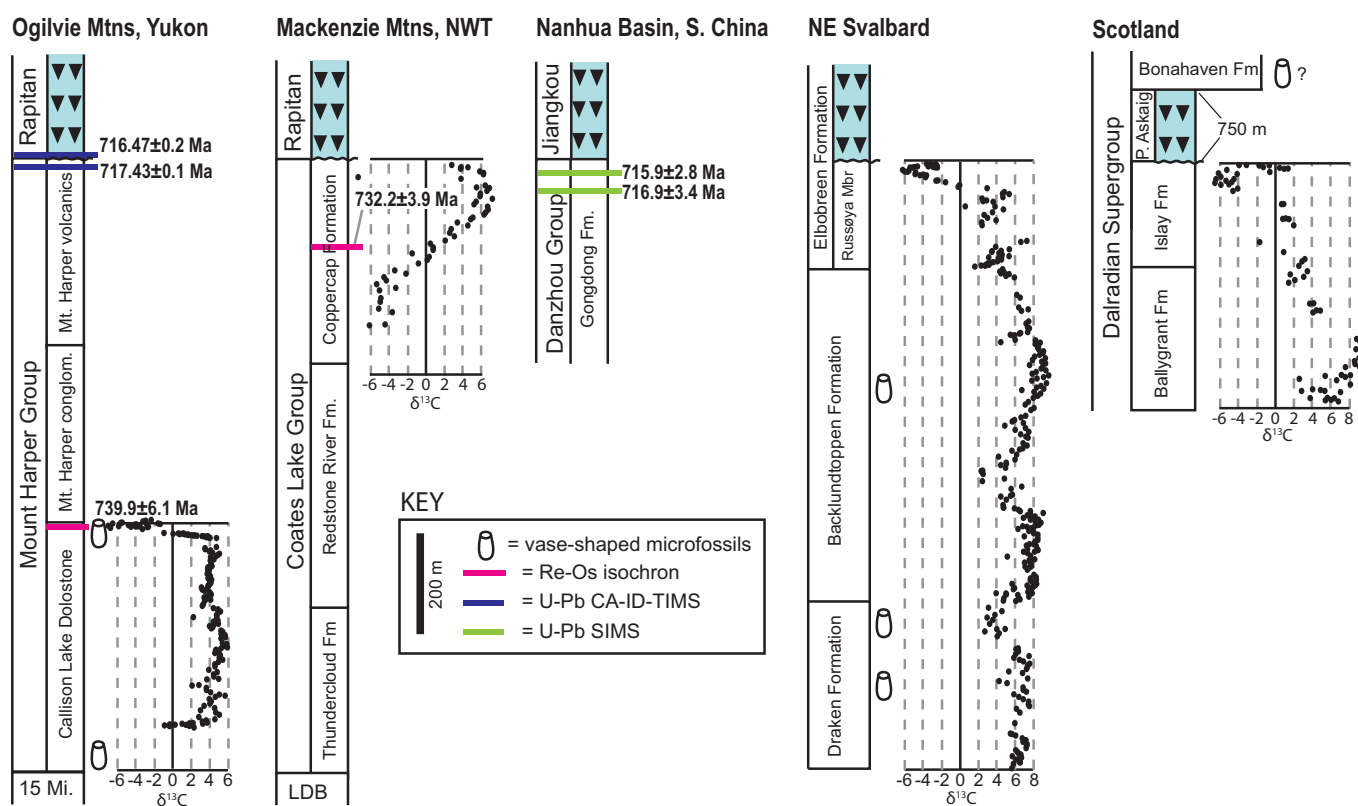


Figure 2: Key successions that provide radiometric constraints and/or biostratigraphic and chemostratigraphic data relevant to the Cryogenian GSSP. Figure based on Strauss et al. (2014), with data from Macdonald et al. (2010) and Strauss et al. (2014) (Ogilvie Mtns); Rooney et al. (2014) (Mackenzie Mtns); Lan et al. (2014) (Nanhua Basin); Knoll et al. (1989, 1991) and Halverson et al. (2005) (Svalbard); and Prave et al. (2009) and Anderson et al. (2014) (Scotland). Meterage for all sections indicated in key.

that the implied carbon cycle perturbation was causally related to the onset of Cryogenian glaciation (Schrage et al., 2002). However, recent Re-Os age constraints imply that the *Islay anomaly* in Scotland (correlated to Greenland, Svalbard and NW Canada) could predate the onset of Cryogenian glaciation by at least 15 million years (Strauss et al., 2014; Fig. 2), and that the Coppercap Formation (Mackenzie Mountains, NW Canada) may preserve a more complete, but still truncated pre-glacial succession.

In the Coppercap Formation, the pre-glacial negative anomaly is followed by a recovery to high positive $\delta^{13}\text{C}$ values that might have been removed by erosion in Scotland and Svalbard. In the Mackenzie Mountains, this $\delta^{13}\text{C}$ recovery is accompanied by decreasing $^{87}\text{Sr}/^{86}\text{Sr}$ from a high of ~ 0.7067 –70 to ~ 0.7065 (Rooney et al., 2014), followed by a modest rise back to ~ 0.7066 –67. The range and trend of $^{87}\text{Sr}/^{86}\text{Sr}$ values are similar in Scotland, but there the negative $\delta^{13}\text{C}$ anomaly does not recover back to high positive values, and it is accompanied by a fall in $^{87}\text{Sr}/^{86}\text{Sr}$ from ~ 0.7066 –70 before the anomaly to $\sim 0.7065 \pm 1$ during the anomaly (Brasier and Shields, 2000; Sawaki et al., 2010). Sparse data from Svalbard exhibit unchanging $^{87}\text{Sr}/^{86}\text{Sr}$ values of ~ 0.7067 before the negative anomaly (Halverson et al., 2007), whereas data from carbonates which postdate the anomaly in East Greenland yielded least altered values of 0.7063–64 (Fairchild et al., 2000). Assuming that these negative excursions all relate to the same pre-glacial *Islay anomaly*, the existing C isotope data support the idea that the Mackenzie Mountains region (and possibly E Greenland sections) provides the most complete of the best-known pre-glacial carbonate successions. However, the Sr isotope record, although generally supportive of mutual correlation between these sections, is ambiguous in its detail. $^{87}\text{Sr}/^{86}\text{Sr}$ values are notoriously susceptible to diagenetic alteration, while C isotope stratigraphy remains untested for much of the Precambrian due to the absence of an adequate biostratigraphic framework. Additional work is needed

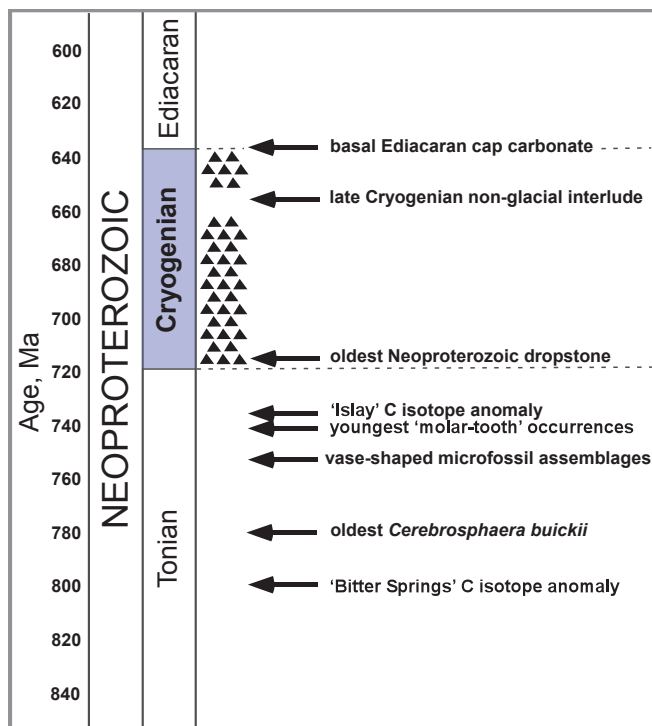


Figure 3. Major events associated with the newly defined Cryogenian Period and the Tonian-Cryogenian interval.

to verify that Sr- and C-isotope trends can be reproduced regionally and globally and that the negative anomaly in the Coppercap Formation is the same as the pre-glacial anomaly found in Svalbard and Scotland.

Despite the focus on chemostratigraphy, a number of fossil groups show potential as global time markers. For example, the appearance of several species of vase-shaped microfossils (VSMs) worldwide between circa 770 Ma and 740 Ma (Figs. 2–3) could provide additional means to correlate and define the onset of the Cryogenian (Porter et al., 2003; Strauss et al., 2014), and slightly older strata preserve distinctive widespread acritarch species that could prove useful (Fig. 3; Porter and Riedman, *in press*).

A prescription for future subdivision of Proterozoic strata?

The newly defined Cryogenian Period began about 720 million years ago and continued until 635 Ma; its shorter c. 95 million-year duration now resembles its Phanerozoic counterparts. One inevitable consequence of this redefinition is that the Tonian–Cryogenian boundary has leaped forward in time from 850 Ma to ca. 720 Ma, rendering the Tonian Period exceptionally long (1000 – ca. 720 Ma). In recognition of the fact that the term ‘Tonian’ refers to the stretching caused by the break-up of the supercontinent Rodinia (Plumb, 1991), which began only after ca. 850 Ma, we consider that the Tonian Period may also undergo radical redefinition, possibly triggering formulation of a new period for the earliest Neoproterozoic.

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