Descent into the Cryogenian

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Abstract

The Cryogenian Period brackets an interval of profound glaciation, commonly referred to by the evocative epithet 'Snowball Earth'. According to its recent redefinition, the Cryogenian began before the onset of low-latitude glaciation ca. 717 Ma and ended during its final and catastrophic melting phase ca. 635.5 Ma. Pending future ratification of a Global Stratotype Section and Point or GSSP, the onset of the Cryogenian Period is estimated at about 720 Ma. However, no consensus has yet been reached concerning the best section or criteria for its definition. The articles in this special issue represent the state-of-the-art in Tonian-Cryogenian transition stratigraphy around the world and will contribute to the selection of the future GSSP.

1. Introduction

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) (Plumb, 1991). However, the discrepancy in age between the basal Cryogenian GSSA at 850 Ma and the onset of widespread glaciation ca. 717 Ma (Macdonald et al., 2010) quickly rendered the previous definition obsolete. For this reason, consensus opinion moved towards the establishment of a rock-based definition of the Cryogenian, beginning near the base of the Sturtian glacial interval and ending at the basal Ediacaran GSSP (Knoll, 2000). The International Subcommission on Neoproterozoic Stratigraphy subsequently proposed that any Cryogenian System would need to begin within an outcrop section at a precisely defined stratigraphic level (GSSP) that was clearly beneath the oldest unambiguously glaciogenic deposits. In 2014 the International Commission on Stratigraphy (ICS) ratified the new rock-based definition, estimating its onset at approximately 720 Ma. The challenge of the current Cryogenian Subcommission is to gather evidence that permits the future establishment of a marker level that meets both the spirit, i.e. bracketing global 'snowball' or near-global 'slushball' (see, for example, Bindeman and Lee, 2017) glaciations, and the fundamental requirements, i.e. facilitating global correlation, of such a definition (Shields-Zhou et al., 2016).

Stratigraphic correlation of Neoproterozoic strata is still largely reliant on the unambiguous identification of glaciogenic strata in any given succession. Independent means of correlation are vitally important, but the fossil record has until recently been too poorly known and taxa too long-lasting to be of much help. It was for this reason that it was considered that proven potential for high resolution C- and Sr-isotope correlation would be essential for the basal Cryogenian GSSP. Although several sections in the world could make such a claim, reliance on carbonate-hosted isotopes is also problematic because this would restrict GSSP candidates to shallow marine successions, which are likely to have been subject to erosional scouring during syn-glacial eustatic sea-level fall. Deeper siliciclastic successions could provide alternative candidates but their potential for global stratigraphic correlation is hampered by the lack of isotopic control. It was for this reason that the Cryogenian Subcommission decided to move the debate forward by soliciting research articles for this special issue that would outline the state-of-the-art for potential GSSP successions, regions and criteria. Additional contributions in this volume highlight advances in our understanding of the temporal relationship between Cryogenian glaciation and oxygenation of the oceans.

2. Biostratigraphy

Although the Cryogenian System is marked by a paucity of fossils, the upper Tonian period (currently defined as 1000 to ca. 720 Ma) is characterised by a relative abundance of eukaryotic fossils, in particular. The taxonomic richness of the late Tonian oceans is confirmed by research outlined in this issue (Riedman and Sadler, 2017), which identifies a peak in organic-walled microfossil (OWM) diversity at ca. 770 Ma. Long-lived taxa, such as *Trachyhystrichosphaera aimika*, intriguingly disappeared just when vase-shaped microfossils (VSMs) began to emerge. In turn, these latter fossil types, widely accepted to be testate amoebae (Porter and Knoll, 2000), disappeared from the record ca. 10–20 myrs before the onset of Cryogenian glaciation (Rooney et al., 2017). Despite having mostly terrestrial counterparts today, Tonian VSMs occur in abundance in a variety of facies in marine strata around the world, and so have great potential for stratigraphic subdivision and correlation. The absence of all known Tonian VSM species from younger strata could become an important characteristic distinguishing Tonian from Cryogenian strata (Riedman et al., 2017).

Species-level VSM biostratigraphy is becoming a possibility with a range of preservation types now known and a distribution across seven different countries. Riedman et al. (2017) constrain the stratigraphic ranges of VSMs worldwide on the basis of published data, a newly described assemblage from Tasmania, and restudy of fossils from Svalbard, Greenland, Sweden and the Yukon. They report here that the first appearance of VSM species—specifically the appearance of *Cycliocyrillium simplex*—postdates the Bitter Springs anomaly (<789 Ma; Swanson-Hysell et al. 2015), but could be older than 759 Ma (based on an equivocal species identification in the Chichkan Formation of Kazakhstan). The most diverse assemblages, including five common co-occurring species that make up the '*Cycliocyrillium simplex* assemblage'—*C. simplex*, *C. torquata*, *Bonniea dacruchares*, *B. pytinaia*, and *Melanocyrillium hexodiadema*—may be a marker for late Tonian time (ca. 740–729 Ma; Riedman et al., 2017). The last appearance of this assemblage immediately underlies a tuff in the uppermost Chuar Group that has yielded a TIMS U-Pb age of 729.0±0.9 Ma (Rooney et al., 2017) and elsewhere either precedes (Svalbard, Greenland and Tasmania) or coincides (Yukon) with the onset of a late Tonian negative $\delta^{13}C$ anomaly in Spitsbergen, Yukon, Greenland and Tasmania. In the Yukon, this level is dated by Re-Os at 739.9 ± 6.1 Ma (Strauss et al., 2014). However, it is unclear whether the pronounced fall in carbonate $\delta^{13}C$ values in the Yukon can be correlated with the so-called 'Islay' anomaly, now referred to as the Garvellach anomaly (Fairchild et al., 2017).

3. Integrated stratigraphy of specific successions

The Garvellach anomaly is discussed further in a comprehensive report of new field- and laboratory-based research on the Tonian-Cryogenian sections of Argyll, Scotland (Fairchild et al., 2017), in which the authors argue for a transitional contact between glaciogenic strata of the Port Askaig Formation and the underlying carbonate platform on the small island of Garbh Eileach. By contrast they report an erosional contact on neighbouring Islay. On Garbh Eileach, carbonate $\delta^{13}C$ values are shown to descend from -4‰ to -7‰ in subtidal limestones before recovering to +1‰ in peritidal dolostones that directly underlie the first evidence for glaciation. If these data reflect the same anomaly as in the Yukon, then this might imply a cryptic ca. 20 million-year disconformity in Scotland despite its apparently transitional character (Fairchild et al., 2017). One possible resolution to this quandary is that there were two late Tonian negative $\delta^{13}C$ anomalies of comparable magnitude (Halverson et al., 2017), with the uppermost only being preserved in regions where subsidence rates were particularly high or syn-glacial erosion very minor. A related paper in the special issue (Ali et al., 2017) provides further evidence in support of a transitional contact and high subsidence rates, based on the exceptional thickness of the succession and their report of 76 climatically related stratigraphic episodes within the Port Askaig Formation (Ali et al., 2017). Clasts through the lower part of the formation exhibit a mirror image of the Garvellach anomaly, which is interpreted to mean that the diamictite represents the progressive unroofing of the regional carbonate platform.

Halverson et al. (2017) document correlative Tonian-Cryogenian successions from NE Svalbard, which have yielded a rich microfossil and chemostratigraphic record. In Svalbard, the stratigraphically highest pre-glacial unit is the Russøya Member, which, interestingly, contains molar-tooth structure (MTS or early diagenetic calcite microspar cement), a deeply negative $\delta^{13}C$ anomaly and the youngest occurrence of VSMs in the succession (the species

Bonniea dacruchares). MTS and unchanging $^{87}Sr/^{86}Sr$ ratios around 0.7067 are also reported from the erosionally truncated Islay succession described by Fairchild et al (2017). Erosional truncation in Svalbard is supported by the occurrence of stratigraphically higher beds in correlative NE Greenland, i.e. Bed Group 20 at Kap Weber (Fairchild *et al.*, 2000; Klaebe *et al.*, 2017), which shows a return to high $\delta^{13}C$ values accompanied by a decrease in $^{87}Sr/^{86}Sr$ to ~0.7063, reminiscent of isotopic features found at Garbh Eileach (Fairchild et al., 2017).

Two NE Greenland successions are described in the special issue and interpreted to be quasi-transitional at both Kap Weber and Ella Ø, despite quite different sedimentary facies of the underlying pre-glacial units (Klaebe et al., 2017). In their study, the authors propose that the lowest glaciogenic deposits at Ella Ø are correlative with erosion and aeolian sand deposition at Kap Weber as glacioeustatic sea level fall exposed the carbonate platform. Their preferred interpretation is that underlying units are coeval, which means that high $\delta^{13}C$ limestones of bed group 20 at Kap Weber formed contemporaneously with low $\delta^{13}C$ marls of the slope facies at Ella Ø.

Greenland is also the focus of another contribution to the special issue (Scheller et al., 2017), in which the redox state of the ocean during the Cryogenian warm interval between ca. 660 Ma and ca. 645 Ma is revealed using a combination of isotopic proxies (Mo, C, S, Fe). The authors conclude that following Sturtian deglaciation, anoxia prevailed generally in the world's oceans, but locally, euxinia dominated. In a related article, Cheng *et al.*, 2017 applied Mo isotopes to potentially correlative strata from South China, and come to a similar conclusion, arguing for delayed ocean oxygenation, despite significant amounts of atmospheric oxygen (Wei et al., 2018).

The Tonian-Cryogenian successions of Yukon, Canada, boast the most robust chronostratigraphic framework to date, with high precision U-Pb ages, an isotope stratigraphic framework, and the potential for VSM-based biostratigraphy (Macdonald et al., 2017). The age constraints for onset of Cryogenian glaciation at low latitudes at ca. 717 Ma (Macdonald et al., 2010) are bolstered by five new high-precision (CA-TIMS) U-Pb zircon ages spanning the onset of the Sturtian (Rapitan) glacial in the Coal Creek inlier. This age is supported by a new U-Pb baddeleyite age of 713.7 ± 0.9 Ma on syn-glacial volcanics from the Tatonduk inlier reported here by Cox *et al.* (2017). Indistinguishable ages have been reported from immediately pre-glacial deep marine successions of South China (Lan et al., 2014; Song et al., 2017).

Although the Tonian-Cryogenian succession in Yukon is unusually complete and well dated, it is difficult to access and the Cryogenian glacial deposits there are generally thinner and less completely developed than in other locations in the Cordillera of western North America. One region with both good access and abundant sections of thick Cryogenian glacial deposits is Death Valley. In this issue, Le Heron *et al.* (2017) present a new, detailed stratigraphic log through perhaps the thickest-yet documented Cryogenian glacial diamictite-bearing succession. Such expanded glacial intervals are important for documenting syn-glacial climate and glacial dynamics, but as noted by the authors, even at 2.4 km-thick, given the long ca. 57 Ma duration of Cryogenian glaciation (Rooney et al., 2015), this section represents very slow sediment accumulation as compared to typical Phanerozoic glaciations (Partin and Sadler, 2016).

4. Quo Vadis: Cryogenian GSSP

The motivation for this special volume was to provide up-to-date data from key successions globally that preserve the Tonian–Cryogenian transition in order to guide future selection of the basal Cryogenian GSSP. Selection of this GSSP is non-trivial and intrinsically more challenging than the basal Ediacaran GSSP because the lower Cryogenian is characterized by the widespread occurrence of an erosional unconformity that juxtaposes clearly pre-glacial strata below with glacial (or even post-glacial) strata above. One guiding principle of international stratigraphy is that a GSSP should lie within a section that represents continuous (or nearly continuous) sedimentation (Remane et al., 1996), which precludes placing the GSSP at the unconformity. Therefore, the GSSP should be placed clearly beneath the oldest unambiguously glaciogenic deposits.

Further criteria will guide the eventual selection of the Cryogenian GSSP, and these can be divided into four categories. These categories are adapted from those of Remane et al. (1996), but follow their four categories of requirements. We have emphasised some categories of especial importance to Precambrian stratigraphy, and note the additional requirement that the chosen GSSP underlie unambiguous evidence for glaciation (Shields-Zhou et al., 2016).

1) Geological requirements:
    a) Good exposure over an adequate thickness and lateral extent of sediment;
    b) Continuous sedimentation across contact (*preferably also into glacials*);
    c) Sufficient sedimentation rate to allow recognition of successive events;
    d) Absence of synsedimentary and tectonic disturbance;
    e) Absence of metamorphic or diagenetic alteration of stratigraphic signatures.

2) Biostratigraphic requirements:
    a) Abundance and diversity of well-preserved fossils;
    b) Diversified and taxonomically distinct cosmopolitan biotas;
    c) Open marine facies with minor facies change around the contact.

3) Other stratigraphic methods:
    a) Proven potential for magnetostratigraphy (of limited application here);

b) Proven potential for cyclostratigraphy (of limited application here);
c) Proven potential for isotope stratigraphy (*especially C and Sr isotopes*);
d) High precision absolute age control.

4) Other requirements:
   a) Likely permanence of marker section and point;
   b) Good accessibility, whereby "*candidate sections in remote regions which can only be visited by organising costly expeditions should normally be excluded from the selection*" (Remane et al., 1996);
   c) Free access for researchers, regardless of nationality

The metamorphic and barren nature of many Neoproterozoic successions, along with the possibility for global isotopic correlation of pre-glacial strata, means that not all of these criteria can be satisfied. For example, fulfilling the essential categories 1 and 4, along with satisfying 2c and 3c, was considered previously to be sufficient to define a globally correlative Cryogenian GSSP, along with the stated additional requirement that the chosen level underlie unambiguous evidence for glaciation. However, recent developments in Tonian biostratigraphy (see categories 2a and 2b) and high precision geochronology (3d), much of which has been highlighted in this special issue, show that other forms of correlation have untapped potential, which may change consensus opinion with time regarding the ideal GSSP.

In table 1, we have attempted to list key successions of interest, several of which are described in more detail in this special issue, together with our subjective opinions on how the relevant sections satisfy the GSSP criteria outlined above. Clearly, no single succession currently satisfies all the requirements of an ideal GSSP, and several successions that satisfy most of the criteria in categories 1–3 do not satisfy the accessibility criterion 4b. Importantly, key papers continue to be published on little known successions (MacLennan et al., 2018), which could in future be proposed as candidate GSSPs and will need to be incorporated into the burgeoning stratigraphic framework for this crucial transition in Earth history.

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Table 1

Potential basal Cryogenian candidate sections around the world listed against ideal GSSP attributes based on the recommendations of the International Commission on Stratigraphy (Remane et al., 1996) and our interpretation of how those might be applied to any future Cryogenian GSSP. The list is not exhaustive but reflects the current state of knowledge as evidenced from papers in this special issue and ongoing discussions within the Cryogenian Subcommission. Column numbering relates to the criteria 1a to 4c listed in the main text. VSMs = vase-shaped microfossils; OWMs = organic-walled microfossils.

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