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# The Laurentian Neoproterozoic Glacial Interval: reappraising the extent and timing of glaciation

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## Abstract

One of the major issues in Neoproterozoic geology is the extent to which glaciations in the Cryogenian and Ediacaran periods were global in extent and synchronous or regional in extent and diachronous. A similarly outstanding concern is determining whether deposits are truly glacial, as opposed to gravitationally initiated mass flow deposits in the context of a rifting Rodinia supercontinent. In this paper, we present 115 publically available, quality-filtered chronostratigraphic constraints on the age and duration of Neoproterozoic glacial successions, and compare their palaeocontinental distribution. Depositional ages from North America (Laurentia) clearly support the idea of a substantial glacial epoch between about 720-660 Ma on this palaeocontinent but paradoxically, the majority of Australian glacial strata plot outside the previously proposed global time band for the eponymous Sturtian glaciation, with new dates from China also plotting in a time window previously thought to be an interglacial. For the early Cryogenian, the data permit either a short, sharp 2.4 Ma long global glaciation, or diachronous shifting of ice centres across the Rodinia palaeocontinent, implying regional rather than global ice covers and asynchronous glacial cycles. Thus, based on careful consideration of age constraints, we suggest that strata deposited in the ca. 720-660 Ma window in North America are better described as belonging to a Laurentian Neoproterozoic Glacial Interval (LNGI), given that use of the term Sturtian for a major Neoproterozoic glacial epoch can clearly no longer be justified. This finding is of fundamental importance for reconstructing the Neoproterozoic climate system because chronological constraints do not support the concept of a synchronous panglacial Snowball Earth. Diachroneity of the glacial record reflects underlying palaeotectonic and palaeogeographic controls on the timing of glaciation resulting from the progressive break-up of the Rodinian supercontinent.

## 1 Introduction

In 2020, the idea of globally synchronous Snowball Earth events during the Cryogenian period (Hoffman et al., 1998; Hoffman and Schrag, 2002) remains a popular idea. The expansion of global scale ice masses excites many geologists, and the notion is now used to explain phenomena such as regional or even global scale unconformities (DeLucia et al., 2018) and patterns of biological evolution (e.g., Brocks et al., 2017). Numerous studies advocate an older ~720-660 Ma 'Sturtian' glaciation and a younger shorter-length ~645-635 Ma 'Marinoan' glaciation, both named after Australian stratigraphy, and both defined by globally synchronous onsets and terminations (Hoffman and Schrag, 2002). Looking at the development of ideas of global glaciation, Eyles and Januszczak (2004) recognized five iterations of snowball Earth in the literature including (i) Agassiz (1840) for die *Eiszeit*, specifically dealing with the Quaternary, (ii) Ramsay's (1926) proposal of "world-wide refrigeration", (iii) Mawson's (1949) recognition of "the world's greatest ice age" in the Precambrian, (iv) Harland's "Infracambrian glaciation" with near synchronous global tillites (1964), and finally (v) the "modern snowball" theory of Kirschvink (1992) and Hoffman et al. (1998). Between these times, skepticism for glaciation has waxed and waned, and the intensity and extent of glaciation has come under scrutiny. Two fundamental aspects are (i) geochronology and (ii) the systematic and detailed evaluation of sedimentary facies. Robust dates are required to support the idea of a global glaciation: with 'the decisive falsifying test' of a Snowball Earth model being chronometry (Hoffman 2011, p. 29). Furthermore, careful and systematic analysis of sedimentary sections and their palaeotectonic setting during deposition is essential to demonstrate the glacial, interglacial, or non-glacial origins of the successions (Allen and Etienne, 2008).

Using Re-Os geochrononology, Rooney et al. (2014) argued that the longest and oldest such Neoproterozoic glaciation (the Sturtian: Macdonald et al., 2010) was of 55 Ma duration, based on sample analyses immediately below and above the Rapitan diamictite of Canada. The use of stable isotope curves is widely used as a correlation tool where absolute dates are not available (e.g Halverson et al., 2010). Allen and Etienne (2008) provocatively proposed that absolute age dates from glacial sequences could be interpreted as recording 6 local phases of glaciation between 780 and 630 million years, based on 14 global radiometric age constraints, recognizing that this was a non-unique solution. The idea of diachroneity in Neoproterozoic glaciations is not new: Kröner (1977) made this claim for African deposits, albeit based on a limited set of Rb-Sr ages.

A major problem with the objective interpretation of Neoproterozoic glaciations, and glacial deposits associated with them, is that discussion is dominated by the model-led approach of Snowball Earth (Hoffman et al., 2017). A specific problem seems to be the tendency to neglect sedimentological details that the model cannot accommodate, and yet which demand rational geological explanation (see, for example: Condon et al., 2002; Arnaud, 2004; Leather et al., 2005; Allen and Etienne, 2008; Le Heron et al., 2011, 2013, Busfield and Le Heron, 2016, 2018). When problems with the model arise, inconvenient evidence is typically not tackled head-on, should this evidence be incompatible. This approach has led to continual adaptation of the hypothesis to new evidence (Allen and Etienne, 2008). It is in this context in which we reappraise the chronometry of the Neoproterozoic glaciations, identify alternative interpretations that honour the available data, and consider the extent to which glacial successions of this age can be confidently correlated on a global basis.

The core of our paper is 115 age constraints which are presented from publically available, peer-reviewed sources, which have been sub-divided on a palaeocontinent-by-palaeocontinent basis (Fig. 1). We propose two plausible explanations of the global geochronological dataset: (i) a short, sharp (2.4 Ma long) glaciation in the early Cryogenian, in direct contrast to prevailing views for a 55 Ma glaciation, and (ii) regionally diachronous glaciations similar to those previously proposed (e.g. Eyles and Januszczak, 2004). Both of these explanations are distinct from both the Snowball and Slushball models (see Fairchild and Kennedy, 2007, for a review). The issue of diachroneity and correlation is also discussed, as is the correlation potential of glacial successions.

## 2 Data and methods

Spence et al. (2016) published the global geochronological constraints on Proterozoic glacial deposits up to December 2015. Mining those data herein, and combining them with data published since, we plotted 115 individual data points on a continent-by-continent basis, showing maximum, minimum, and depositional ages for such units (Fig. 1). Data from abstracts and extended abstracts were discarded due to lack of evidenced scrutiny and peer-review. This approach resolves the issue of so-called "rumourchrons" or situations where two or more versions of the same age constraint are publically available (typically resulting from data or sample reprocessing between conference abstract submission and the associated peer-reviewed paper emerging subsequently). Using the same reasoning, we have also discarded dates from secondary sources, i.e. those papers relying on age data published in abstracts only. On the plot, we display error bars for each point and also colour-code the geochronometric data source (Re-Os, U-Pb TIMS, U-Pb SHRIMP, PbPb TIMS, paired U-Pb and Lu-Hf, K-Ar, Rb-Sr, Ar-Ar hornblende, Sm-Nd Th-U-Pb and Sm-Nd). Geochronological constraints are available from nine discrete regions (Sao Francisco / Congo Craton, Kalahari Craton, North China, South China, Arabia / Nubia, Australia, Laurentia, Avalonia and West Africa). These are widely regarded as tectonically separate entities during the Neoproterozoic (Li et al., 2013). Throughout this paper the temporal duration of proposed snowball Earth intervals follows the scheme of Rooney et al. (2015).

### 2.1 Data descriptions

The following descriptions refer exclusively to Fig. 1. With a single exception (Cox et al., 2018), it is apparent that all Australian data points fall *outside* the proposed "Sturtian" panglacial time band of Rooney et al. (2015). Indeed, aside from two data points in South China (Lan et al., 2014; Zhou et al., 2004: points 6 and 7 respectively, South China bin), a single data point in Oman (Bowring et al., 2007: point 10, Arabia/Nubia bin- incorporating resampled material of Brasier et al., 2000), and one in Mongolia (Rooney et al., 2015: point 31, Laurentia bin), the only continent that demonstrably yields "Sturtian" age dates is Laurentia. There, a swathe of maximum age constraints (mostly from U-Pb TIMS zircon dates) cluster in the 780-720 Ma time window; some depositional ages are provided by ash beds (Fanning and Link, 2004; Lund et al., 2003). The youngest date from the "Sturtian" in North America is 662.4±4.6 Ma (Rooney et al., 2014). It is also evident that no dates of "Sturtian" age are evident from the Kalahari, North China, Avalonia or West African cratons despite the supposed globally-synchronous extent of that glaciation (Hoffman, 2011 and refs therein). It is immediately apparent that North American rocks provide the firmest age constraints on Neoproterozoic glaciation (particularly Canada: Rooney et al., 2014).

In Australia, depositional ages extend from the end of the Sturtian to the beginning of the Marinoan as defined by Rooney et al. (2015). In China, Zhou et al. (2004) reported a syn-depositional age of 662.9±4.3 Ma from an ash bed in the Datangpo Formation below the Nantuo glacial deposits, arguing for a Marinoan age. The plot shows that this date (point 8 in the South China bin) is much older than the contact between the supposedly Sturtian glacial deposits and the Tindelpina Shale in the Flinders Ranges based on the syn-depositional, Re-Os analyses of Kendall et al. 2006 (643.0 ± 2.4 Ma) (point 7 in the Australia bin).

On the Arabia / Nubia palaeocontinent, the syn-depositional 711.5±0.3 Ma age (Bowring et al., 2007: Arabia / Nubia bin, point 10) is particularly noteworthy as occurring very early in the Sturtian, which seems problematic in the framework of a Snowball Earth model where the bulk of sedimentation is predicted to occur during final deglaciation under a warming climate (Allen and Etienne, 2008). Moreover, the felsic ash beds that yield this date occur deep in the Abu Mahara stratigraphy beneath a thick succession of intercalated glacial diamictites and non-glacial siliciclastics (Allen and Etienne, 2008).

## 2.2 Data interpretation

Rooney et al. (2011) argued that a 659.6±10.2 Ma depositional age for pre-glacial Ballachulish Slate in Scotland (point 25, Laurentia bin, Fig. 1) "strongly suggests that the Port Askaig Formation may be correlative with the ~650 Ma end-Sturtian glaciations of Australia". By direct comparison, a Re-Os age of 657.2 ± 5.4 Ma was provided by Kendall et al. (2006) for the basal postglacial shales of the Aralka Formation in central Australia, who also obtained another age of 643.0 ± 2.4 Ma from the lithostratigraphically equivalent Tindelpina Shale Member in South Australia. Appraising the global data set, a panglacial of just 2.4 Ma in duration could thus be proposed (whereby 659.6-657.2= 2.4 Ma), a very short "flash in the pan" glaciation contrasting with the 58 Ma duration proposed elsewhere (Cox et al., 2018). This very short time span contrasts vividly with the established, widely-held view of a long-lived Sturtian panglaciation (Macdonald et al., 2010; Rooney et al., 2014, Hoffman et al., 2017, Cox et al., 2018) on multiple continents and oceans (Rooney et al., 2015). However, given the absence of depositional ages from within the posited 55 Ma glaciation time window (Fig. 1), an equally credible interpretation is that there simply are no glacial deposits belonging to the "Sturtian" time band as defined in Rooney et al. (2014) in Australia.

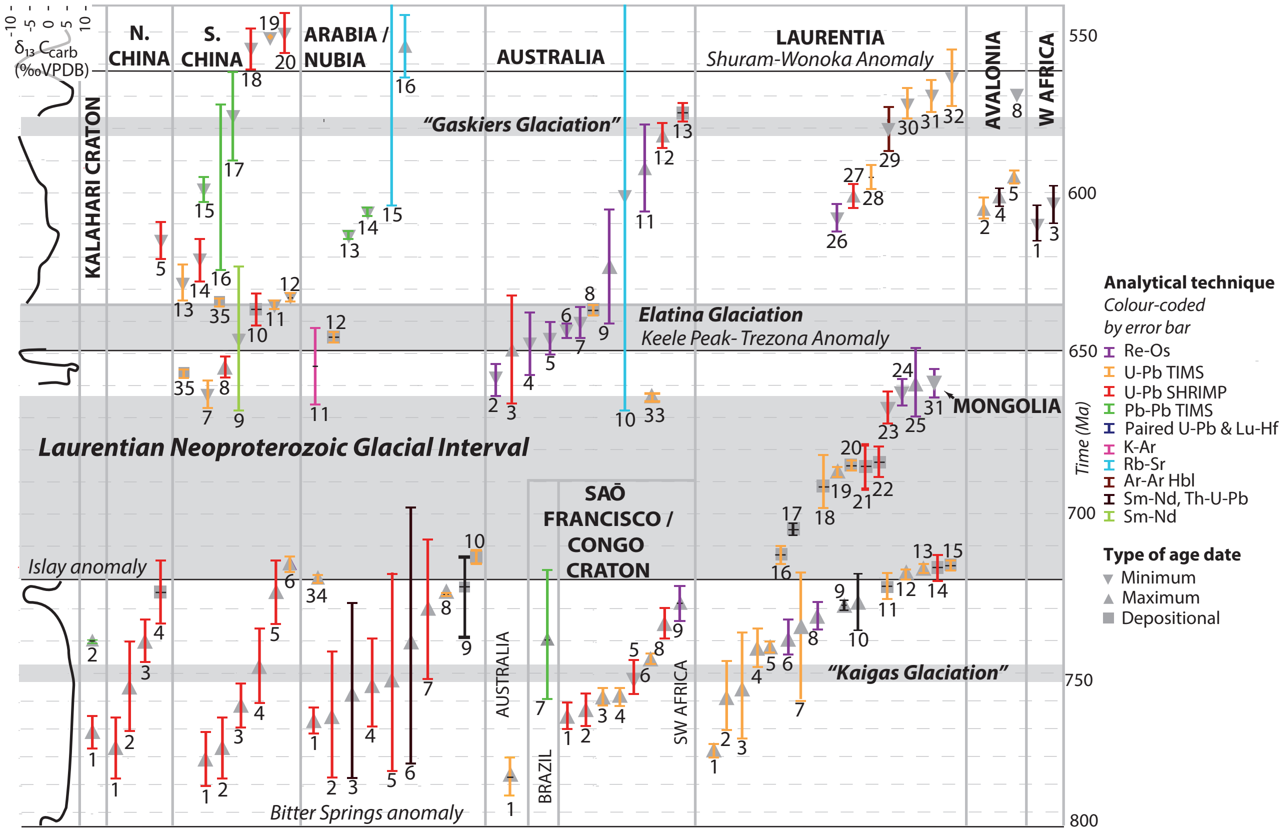

**Fig. 1.** Plot showing available ages of Neoproterozoic diamictites determined through a variety of different methods and plotted according to Neoproterozoic continental blocks / cratons. Data sources as follows. AVALONIA AND WEST AFRICA: (1) Lahondère et al. (2005); (2) Krogh et al. (1988); (3) Lahondère et al. (2005); (4) Kaye et al. (1980); (5) Thompson et al. (2000); (8) Thompson and Bowring (2000). LAURENTIA: (1) Jefferson et al. (1989); (2, 30, 32) Aleinikoff et al. (1995); (3) Ross and Villeneuve (1997); (4) Kalstrom et al. (2000); (5) Fetter and Goldberg (1995); (6) Strauss et al. (2014); (7) McDonough and Parrish (1991); (8, 24) Rooney et al. (2014); (9) Tollo and Aleinikoff (1996); (10) Evenchick et al. (1984); (11) Heaman et al. (1992); (12) Cox et al. (2015); (13, 15) Macdonald et al. (2010); (14, 23) Fanning and Link (2004); (16) Denyszyn et al. (2009); (17) Tollo and Aleinkoff (1996); (18) Ferri et al. (1999); (19) Condon and Bowring (2011); (20) Keeley et al. (2013); (21, 22) Lund et al. (2003); (25) Rooney et al. (2011); (26) Kendall et al. (2004); (17) Dempster et al. (2002); (28) Halliday et al. (1989); (29) Link et al. (1993); (30) Colpron et al. (2002). AUSTRALIA: (1) Preiss et al. (2009); (2, 4, 5, 6) Kendall et al. (2006); (3) Ireland et al. (1998); (7) Kendall et al. (2009); (8) Calver et al. (2013); (9, 11) Schaefer and Burgess (2003); (10) Preiss (1987); (12, 13) Calver et al. (2004); (33) Cox et al. (2018). ARABIA / NUBIA: (1, 2, 4, 5, 7) Ali et al. (2010); (3, 6) Tadesse et al. (2000); (8, 10, 12) Bowring et al. (2007); (9) Brasier et al. (2000); (11) Gorin et al. (1982); (13, 14) Miller et al. (2003); (15, 16) Dureuilh et al. (1992); (34) MacLennan et al. (2018) SAO FRANCISCO, CONGO: (1) Key et al. (2001); (2) Key et al. (2001); (3) Halverson et al. (2005); (4) Hoffman et al. (1996); (5) Borg et al. (2003); (6) Hoffman et al. (1996); (7) Babinski et al. (2007); (8) Key et al. (2001); (9) Rooney et al. (2015). KALAHARI: (1) Frimmel et al. (2001), (2) Frimmel et al. (1996) NORTH CHINA: (1) Yin et al. (2005); (2) Xu et al. (2005); (3, 4, 5) Xu et al. (2009). SOUTH CHINA: (2, 3, 22) Yin et al. (2005); (4) Li et al. (2003); (5) Ma et al. (1984); (7) Zhang et al. (2008); (8) Lan et al. (2014); (9) Zhou et al. (2004); (10, 12) Zhang et al. (2008); (11) Yang et al. (1994); (13, 14, 21) Condon et al. (2005); (15) Yin et al. (2005); (16, 20) Zhang et al. (2005); (17) Barfod et al. (2002); (18) Chen et al. (2004); (19) Chen et al. (2004); (35) Zhou et al. (2019)

Paradoxically, the data indicate that there is much stronger geochronological evidence for "Sturtian" (sensu Rooney et al., 2014) time band deposits in North America (Laurentia) than in Australia, where only a single depositional age (Cox et al., 2018; point 31 in the Australia bin on Fig. 1) plots toward the very top of the "Sturtian" time window. At least five major tectonic events associated with the breakup of Rodinia are now recognized in the plate tectonic models of Merdith et al. (2017), which can be summarized as follows. These are (i) displacement of the Congo-São Francisco cratons between ca. 850-800 Ma, (ii) initial Rodinia breakup in the window 800-750 Ma, (iii) rifting of the Congo-São Francisco cratons at 750-700 Ma, (iv) Kalahari rifting at 700-600 Ma, and (v) opening of the Iapetus from ca. 600 Ma. Thus, the interval containing abundant evidence for glaciation continues to be recognized as one characterized by protracted, pulsed rifting and supercontinent fragmentation, as emphasized in the Zipper Rift hypothesis (Eyles and Januszczak, 2004) where accommodation (and thus depositional ages) are controlled by tectonics. Specifically, the clustering of depositional age dates in the 780-720 Ma time window is consistent with initial Rodinia rifting and rift basin formation, and the potentially continuing far field effects of the Congo-São Francisco craton breakup thereafter (Merdith et al., 2017).

The above analysis leads to the conclusion that the continued use of the term "Sturtian" to refer to a major worldwide glacial interval can no longer be justified. It has been long since pointed out that the term Sturtian was applied to a specific chronostratigraphic subdivision in the Adelaide fold belt of South Australia (see Preiss et al., 2011 for a review), because it contained, among other rocks, the deposits of Sturt Gorge outside of Adelaide (Mawson and Sprigg 1950). Owing to the current lack of a GSSP for the Cryogenian, which may be resolved in the near future (Shields et al., 2018), we feel it is currently inappropriate to try to establish further formal terminology to apply to events or glaciations within the Cryogenian period on the basis of supposed global synchroneity of glaciation. It is recommended that the term "Sturtian" should now be applied only to the appropriate rocks of Australia. In the meantime, to avoid the potential for confusion, we advocate the informal term "Laurentian Neoproterozoic Glacial Interval" (LNGI) to describe the episode of glaciation recorded in and affecting North America, and loosely comparable to the Sturtian time band in Rooney et al. (2015). This informal term is appropriate because it refers to well-studied glacial deposits from which there are a series of independent age constraints, and does not include reference to problematic rocks for which few age constraints are available.

## 3 Discussion and implications

The current drive to find a suitable Global Section Stratotype and Point (GSSP) for the Cryogenian (Shields et al., 2018), renders the discussion of the extent and posited synchronicity (e.g. Rooney et al., 2015, Cox et al., 2018) of Cryogenian glaciations very pertinent. To many, this is an uncomfortable discussion given the neat two-fold Sturtian and Marinoan glaciations which are popularly proposed (Evans, 2000). This two-fold subdivision has long been shown on publications (Hoffman et al., 2017), even however when those publications plot age constraints with wide error bars (Evans, 2000). The plots presented here, in contrast, permit alternative interpretations that are faithful to the data in 2020. Two plausible alternatives adequately explain the global trends seen on this plot. The first is one of a short, sharp older Cryogenian glaciation of 2.4 Ma in duration; the second model proposes a diachronous older Cryogenian glaciation that is best expressed on Laurentia, the Laurentian Neoproterozoic Glacial Interval (LNGI) proposed here. Owing to the need to "force fit" data from multiple continents to a "Sturtian" model, we place the short, sharp glacial model to one side. The recognition of an LNGI is significant for a number of reasons. Firstly, the Laurentian record provides excellent age constraints from the Yukon (Rooney et al., 2015). Secondly, alongside the Port Askaig Formation (in Scotland), and the Danzhou Group (China), Shields et al. (2018) identify the Kingston Peak Formation of Death Valley- one of the best Laurentian diamictite outcrop belts in terms of exposure- as having potential as a GSSP. Note that the analysis herein does not exclude the existence of other regional glaciations occurring within the LNGI time window.

Deposits of the LNGI contain persuasive evidence for glacially-influenced marine sedimentation in multiple basins. The Port Askaig Formation contains abundant dolostone lonestones in laminated mudstone (Fig. 2A) that are best interpreted as ice-rafted dropstones (Ali et al., 2018). On mainland Scotland, granite dropstones punctuating and piercing laminated mudstones and sandstones attain boulder size (Fig. 2B) in the Macduff Boulder Beds. In Utah, the Mineral Fork Formation represents the approximate stratigraphic equivalent of the Kingston Peak Formation and exposes exquisite dropstones on Antelope Island (Fig. 2 C). Other intervals of massive diamictite from the same formation (Fig. 2D) are much more ambiguous.

The most demonstrative evidence for both glaciation and tectonics is found in the Kingston Peak Formation of Death Valley, California, which provides a number of excellent lessons for understanding the true relationship between Neoproterozoic glaciation and extensional basin tectonics. Here, evidence of a tectonic control on glaciation becomes evident at a number of scales. At the same time, there are a number of diamictite-rich/bearing sections, at multiple stratigraphic intervals, which are commonly assumed to be glaciogenic but can be demonstrated to derive from local slope collapse. In the Saddle Peak Hills (Fig. 2E) some diamictites are interpreted as platform collapse facies (Creveling et al., 2016; Le Heron and Vandyk, 2019) rather than of glacial origin. This is because the abundant dolomite clasts contain very peculiar facies including tubestone structures and laminites that are restricted to cap carbonate deposits, illustrating that diamictites and the Noonday Dolomite

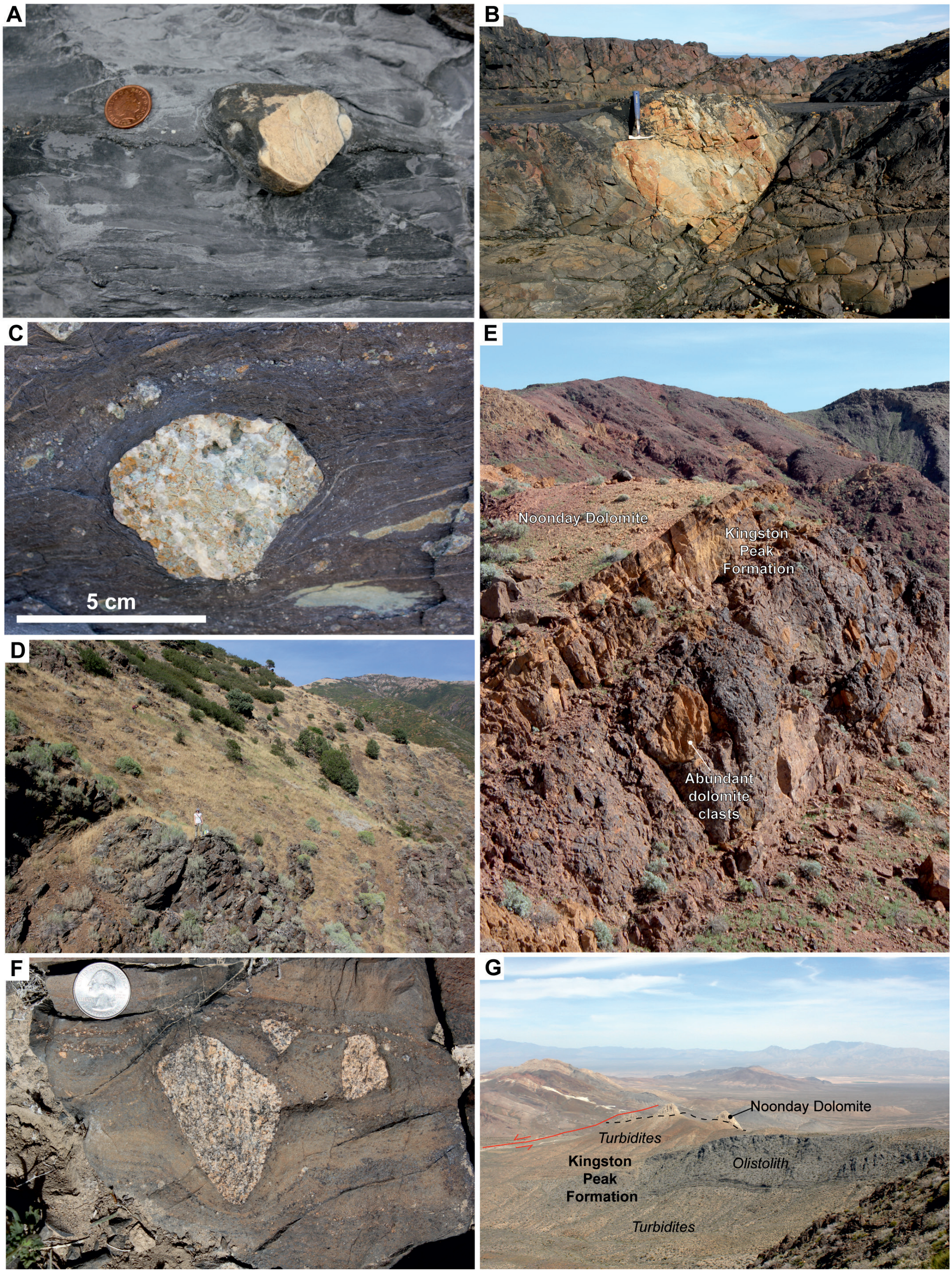

**Fig. 2.** Examples of glacial and non-glacial facies from diverse Laurentian outcrops associated with the Laurentian Neoproterozoic Glacial Interval (LNGI). A: Dolostone lonestone, interpreted as a dropstone, from the Port Askaig Formation, Garbh Eilach, Scotland. This formation records dozens of ice margin oscillations (Ali et al., 2018). B: Granite boulder from the Macduff Boulder Beds, northern Scotland. These deposits represent ice distal sedimentation, with occasional emplacement of ice rafted debris in a marine basin (Busfield and Le Heron, 2018). C: Granite lonestone, interpreted as a dropstone, from the Mineral Fork Formation, Antelope Island, Utah. D: Thick, stacked, boulder-rich diamictites from the Pocatello Formation, Idaho. Though a lateral continuation of the Mineral Fork Formation, their origin (glacial vs non-glacial) remains ambiguous. E: The contact between diamictites of the Kingston Peak Formation and the overlying Noonday Dolomite in the Saddle Peak Hills, Death Valley. These particular diamictites are known to contain fragments of carbonate laminites and tubestones- an identical facies that is exposed in the overlying Noonday Dolomite (Creveling et al., 2016). F: More convincing evidence for a glacial influence on sedimentation from the Salt Spring Hills, Death Valley, also from the Kingston Peak Formation. Trains of lonestones, interpreted as dropstones, are well exposed. G: Scale of observation greatly affecting perspective in the Kingston Peak Formation in the Kingston Range type area. A 500 m wide dolostone block derived from underlying strata is encased within turbidites, and interpreted as an olistolith (Macdonald et al., 2013, Le Heron et al., 2014).

are laterally equivalent facies (Creveling et al., 2016). The same story is played out in the type section in the Kingston Range, where huge megaclasts interpreted as olistoliths (Macdonald et al., 2013; Le Heron et al., 2014) are encased in well-organised turbidites with occasional dropstone-bearing intervals (Fig. 2G). Nevertheless, there are abundant sections where excellent dropstones are recognized (Busfield & Le Heron, 2016; Le Heron & Busfield, 2016), and where glacial influence on sedimentation is beyond reasonable doubt (Fig. 2F). In spite of this, there remains a paradox concerning the rate of sediment supply. Attempts to quantify accumulation rates associated with Cryogenian glaciations have led to the conclusion that Cryogenian accumulation rates were 4 to 15 times slower than for comparable Phanerozoic glaciations (Partin and Sadler, 2016). These conclusions provide fertile ground for considering ice dynamics, yet they are underpinned by an assumption of 5 Myr and 57 Myr durations for the Marinoan and Sturtian glaciations respectively. Even if a global, "Sturtian" glaciation is dismissed and the LNGI recognised instead, then it remains unchanged that sedimentation rates were low.

In the context of the LNGI, detailed investigation of the Kingston Peak Formation in Death Valley from multiple outcrop belts (Fig. 3) has revealed how variable the diamictite-bearing deposits are, recording multiple glacial cycles that cannot be correlated between individual basins (Le Heron et al., 2017, 2019). This is thought to be because the ice masses waxed and waned asynchronously, and deposited a record intimately mixed with tectonically driven slope collapse debris and olistostromes (Le Heron et al., 2019). In this regard, Kennedy and Eyles (2020) emphasize the importance of tectonically-driven basin margin collapse and mass flow events in generating debrites previous reported as 'glacial diamictites' and 'tillites' that are non-glacial 'tectonofacies' produced by downslope mixing of coarse and fine sediment. These workers emphasized the importance of applying a 'tectonosequence' approach in contrast to the simple bed-by-bed climatostratigraphic models of earlier workers. Other investigations in Congo has similarly demonstrated the fundamental importance of a tectonic driver on facies types in Neoproterozoic rift basin fills, especially in promoting the accumulation of the 'diamictite/turbidite association' that is characteristic of this interval globally where diamictites commonly approach 1 km in thickness (Kennedy et al., 2018; Kennedy and Eyles, 2019). This work also demonstrates that comparison of very detailed sedimentary logs in terms of facies, clast composition and stratigraphic stacking patterns permit no correlation whatsoever even over a few hundred metres (Tofaif et al., 2019), with major implications for identifying "type sites".

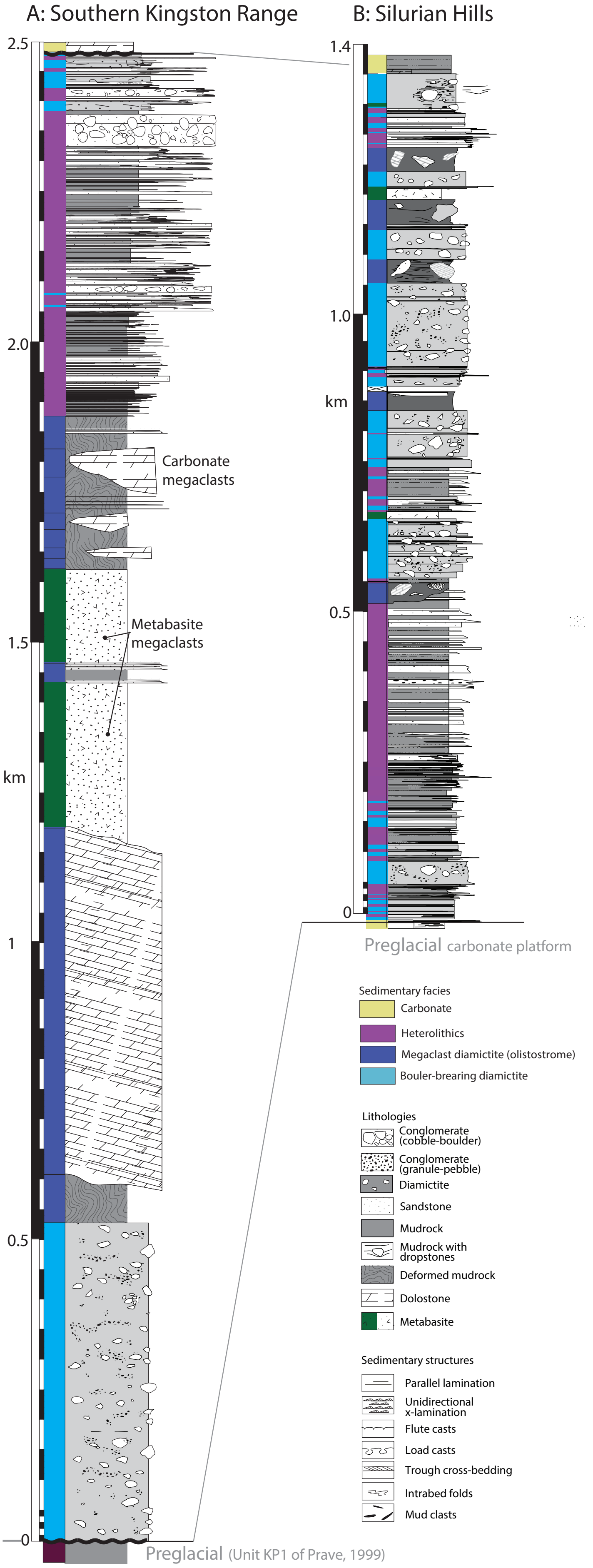

**Fig. 3.** Logged sections from both the Silurian Hills and Kingston Range outcrop belts in the Death Valley region, from Le Heron et al. (2019). Log from the Silurian Hills originally published in Le Heron et al. (2017), and log from the Kingston Range originally published in Le Heron et al. (2018). The comparison highlights that correlation is impossible between neighbouring sub-basins.

With their basis in detailed sedimentological work and consideration of the local basinal setting, the above considerations underscore how the long-suspected intimate association between rifting and glaciation in Death Valley (Prave, 1999) is correct, how these processes conspire to produce a differing record between sub-basins, and how they allow specific questions to be raised about representativeness of the Cryogenian record. These questions extend to all areas on Earth where Neoproterozoic sedimentary successions are exposed. The importance of tectonically driven mass flow sedimentation in the Grand Conglomérat of the Congo Basin has now been recognized in which the primary evidence for glaciation is weak (Kennedy et al., 2018). Arguably the greatest issue is how to evaluate the significance of glacial cycles in the rock record. Further afield, in South Australia, Busfield and Le Heron (2014) demonstrated the applicability of sequence stratigraphy to unravel the nature of glacial cycles in the Cryogenian record, leveraging the glacial sequence stratigraphic methodology of Powell and Cooper (2002) that had been developed for temperate glaciated margins. This methodology is appropriate owing to the apparent lack of syn-sedimentary tectonism in this study area. Other examples, such as the Port Askaig Formation in Scotland, may also be suitable for this approach. In the Port Askaig, no less than 28 glacial cycles (Ali et al., 2018) are recognized, raising serious questions about how, if at all, these cycles can be correlated across palaeocontinents. Establishing which of these cycles represents major glaciation, as opposed to minor ice margin oscillation, remains a goal that is currently out of reach. Coupled with the clear influence of tectonics in compartmentalizing extensional basins, it is suggested that meaningful correlation at an interbasinal level is premature. These stratigraphic and sedimentological considerations underpin the view that the geochronological data must be interpreted more openly to understand the nature, extent, and intensity of glaciation.

## 4 Conclusions

Based on review of the available peer-reviewed geochronological database, we suggest that older Cryogenian glaciations are asynchronous, amplifying the earlier interpretations of Allen and Etienne (2008). In 2020, the available evidence supports a model of diachroneity and provinciality in Neoproterozoic glaciations, and an interpretation that indicates that the Snowball Earth hypothesis can now be objectively placed aside. Diachroneity reflects underlying palaeotectonic and palaeogeographic controls on the timing of glaciation associated with the progressive breakup of the Rodinian supercontinent (Eyles and Januszczak, 2004; Merdith et al., 2017). We propose that the term "Sturtian" should now be used exclusively for the Australian strata, because it derives from Australian sections where chronometry remains poor in spite of recent progress (Cox et al., 2018). Instead, we suggest that the term Laurentian Neoproterozoic Glacial Interval (LNGI) is adopted, which refers to a regional but well constrained interval in present day North America between 720 and 660 Ma.

## 5 Acknowledgments

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