Sedimentary challenge to Snowball Earth

Evidence from the magnetic field fossilized in sedimentary rocks suggests that, more than 600 million years ago, ice occupied tropical latitudes. A popular explanation for these findings, the Snowball Earth concept, envisages a fully frozen Earth for millions of years, caused by a runaway ice–albedo feedback. A rapid, catastrophic meltback at very high levels of atmospheric carbon dioxide is thought to have ended this extreme climatic state. However, sedimentary rocks deposited during these cold intervals indicate that dynamic glaciers and ice streams continued to deliver large amounts of sediment to open oceans throughout the glacial cycle. The sedimentary evidence therefore indicates that despite the severity of glaciation, some oceans must have remained ice-free. Significant areas of open ocean have important implications for the survival and diversification of life and for the workings of the global carbon cycle.

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Over the past decade there has been an exponential growth of papers devoted to the geology of the Neoproterozoic era (1,000–542 million years ago; Myr) in general and to the 'Snowball Earth' hypothesis specifically. This has enlivened the debate of climate change in 'deep time', because a profoundly glaciated Earth serves as an example of environmental change at the limit. Proponents of the Snowball Earth hypothesis[1–3] believe that the Earth froze over completely on one or more occasions during the period that is appropriately called the Cryogenian (approximately 840–635 Myr ago).

A number of observations were connected to form the original idea of a Snowball Earth[1] and its subsequent elaboration[2,3]. Chief among these were the occurrence of glaciation at a low latitude based on palaeomagnetic data; the common occurrence of carbonate rocks—normally indicative of warm water—directly above glacially derived sedimentary rocks, thereby indicating rapid climatic warming following an ice age; and the occurrence of oceanic iron-rich deposits, thought to reflect the existence of anoxic ocean waters during a long period of ice cover.

The essence of the Snowball Earth concept is the growth of ice sheets towards the equator under an ice–albedo feedback on a planet with a 6% lower solar constant compared with today, leading to a globally frozen Earth. Carbon dioxide emissions from volcanoes over very long periods of time (approximately 10^7 years) are envisaged to have built up atmospheric greenhouse conditions, as drawdown of CO_2 by terrestrial weathering of silicate rocks would be negligible. At atmospheric CO_2 concentrations several hundred times the present-day level, the ice covering the surface of the Earth is believed to have melted catastrophically in a 'super-greenhouse', leading to the widespread deposition of oceanic carbonate sediments as sea levels rose rapidly. The enhanced carbonate and silicate weathering during the transient post-glacial period is used to explain the characteristically negative carbon isotope ratios in these carbonate rocks by driving a flux of alkalinity into the world's oceans[2].

The idea of a complete global glaciation is not new, having been initially suggested by the Swiss natural scientist Louis Agassiz in 1837, who used the term "*die Eiszeit*" for a great ice age that covered the Earth and killed all life, after which species were regenerated. The compilation of observations identifying ancient glacial deposits on all of the present-day continents allowed the idea of a great 'Infracambrian glaciation' to be established[4,5].

The modern concept of Snowball Earth dates from the realization that glacial deposits in South Australia, and the carbonate rocks that occur immediately above them, must have been deposited in low latitudes. This realization was made possible because very old sedimentary rocks associated with Neoproterozoic glaciations contain a magnetic field that was imparted at the time of deposition. On the basis of the inclination of the fossilized magnetic field, researchers concluded that ancient glaciations must have taken place at low latitudes[1,6–10]. This conclusion, with the Elatina Formation of South Australia as the benchmark study—one that passes all the reliability tests for the recovery of the magnetic field present at the time of deposition[11]—has not been fundamentally challenged since. It provided the seed for the growth of a further wave of *Eiszeit* thinking; this time placed in an exciting Earth system science context by incorporating aspects of geochemistry[2,3]. Similarly to its precursors, this modern concept of *Eiszeit* has attracted criticism[12–14]. Although one viewpoint is that such a challenging idea will take time to become generally accepted[15], others believe that the idea is fatally flawed.

THE SNOWBALL EARTH IDEA

Since its proposal, many facets of the Snowball Earth concept have been investigated. There has been considerable debate on the number of glaciations, their timing and duration; the palaeolatitudes at which glaciation at sea level took place based on new palaeomagnetic data

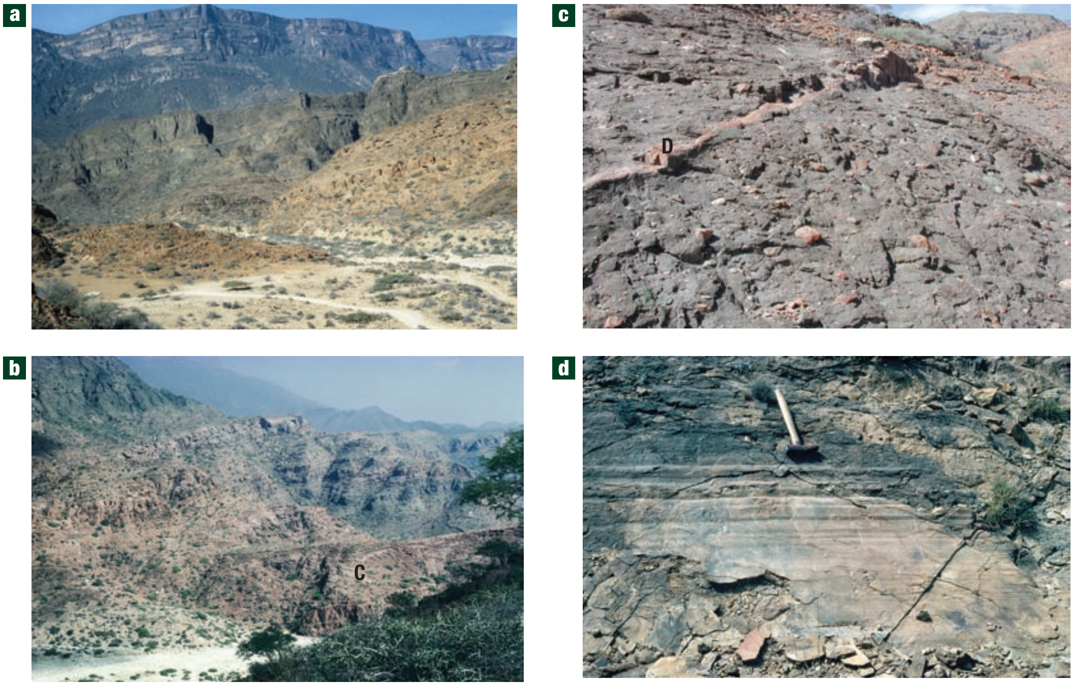

Figure 1 Glacial and non-glacial sedimentary rocks from the Mirbat Group of Dhofar, southern Oman. **a**, Non-glacial, fluvial, deltaic and shallow marine deposits (light brown, foreground) alternating with thick (<200-m-thick) diamictites (dark grey, middle ground) thought to be due to the dropping of debris from floating ice, and the deposition of glacially transported debris near the ice grounding line. Such large-scale alternation requires repeated ice advance and recession. The high cliffs in the background are Cretaceous carbonates. **b**, At the base of the non-glacial succession (brown) are large simple clinoforms (C), indicating the progradation of deltas into proglacial lakes or sea. **c**, Typical appearance of clast-poor diamictites interpreted as due to rain-out from floating ice, with a sandstone-filled dyke (D) due to later injection. **d**, Glacial striations on a siltstone bedding plane, demonstrating ice contact on a subglacial sedimentary substrate. All of these features point to a dynamic glacial regime during a prolonged glacial–interglacial epoch.

and the possible role of high obliquity of the ecliptic (the Earth's axial tilt); the impact of the possible clustering of continental masses in relatively low latitudes; the sedimentary characteristics, structures and isotopic geochemistry of the unusual carbonate rocks that lie directly above glacially influenced sediments; the climate modelling of the descent into, and escape from, a global frozen condition; the modelling of the global carbon cycle; and the importance of oceanic iron deposition.

These different facets are all pertinent to the understanding of the Neoproterozoic Earth system, and have been reviewed, at least partially, before[16,17]. The irreducible feature that the Snowball Earth concept hinges on is the requirement for a truly global ice cover, save for the occasional 'pool' or 'oasis', that effectively sealed off the world's oceans from the atmosphere for a prolonged period—of the order of 10 million years. In the Snowball Earth hypothesis, this allows atmospheric CO_2 concentrations to build up gradually from volcanic emissions and to reach the extremely high levels (perhaps several hundred times present levels) that are needed to trigger sudden, catastrophic melting in a super-greenhouse, notwithstanding some consumption of CO_2 by submarine weathering of new ocean crust[18].

A range of models simulate the collapse into, and escape from, global glaciation—or the stability of a 'near-snowball' or 'slushball' Earth—with particular attention paid to the levels of atmospheric CO_2 required to promote these climatic states[18–29]. Despite the intensity of climate modelling devoted to understanding the glaciations of the Cryogenian, wherein the effects of reduced solar luminosity[30]; increased rotation rate[30]; high planetary obliquity[31–33]; different atmospheric CO_2 concentrations[21]; different palaeogeographical and palaeotopographical configurations governed by plate tectonics[30,34,35]; different ice–albedo feedbacks[36,37]; incorporation of ocean circulation and heat transport[37,38]; and sea ice dynamics[39] have all been investigated, there is no consistent explanation of Cryogenian climate change. Models variously support the collapse into, and exit from, prolonged, Snowball-type global glaciation, some simulate pronounced glaciation on low-latitude land masses under high obliquity, and others show that partial glaciation with open tropical oceans is plausible.

The novelty and attractiveness of the collection of ideas labelled Snowball Earth is that a range of formerly disparate observations are brought together into one framework. The collection of diverse observations and paradoxes into a single unifying idea had the effect of galvanizing the geological and climate science communities. But a falsifying test of the Snowball Earth idea has proved difficult to perform. One test of the proposal of full, global glaciation can be made by considering sedimentological and stratigraphic data.

ENVIRONMENTS AND PROCESSES IN THE NEOPROTEROZOIC ICEHOUSE

Although disagreement remains regarding the precise influence of glaciation recorded in sedimentary rocks deposited during the Neoproterozoic[40,41], many workers have presented a sufficient inventory of sedimentary characteristics to support the contention of a profound icehouse in that era. Evidence for glaciation is abundant in the sedimentary record of the Neoproterozoic[5] (Fig. 1), but the task of discriminating glacial influence is challenging. It is hampered by the fact that glacigenic sediments commonly consist of poorly sorted material including pebbles, cobbles and boulders that are set in a finer grained matrix, called diamictites (Fig. 1c). However, these features are also common to mass flow deposits such as debrites, which lack any glacial influence.

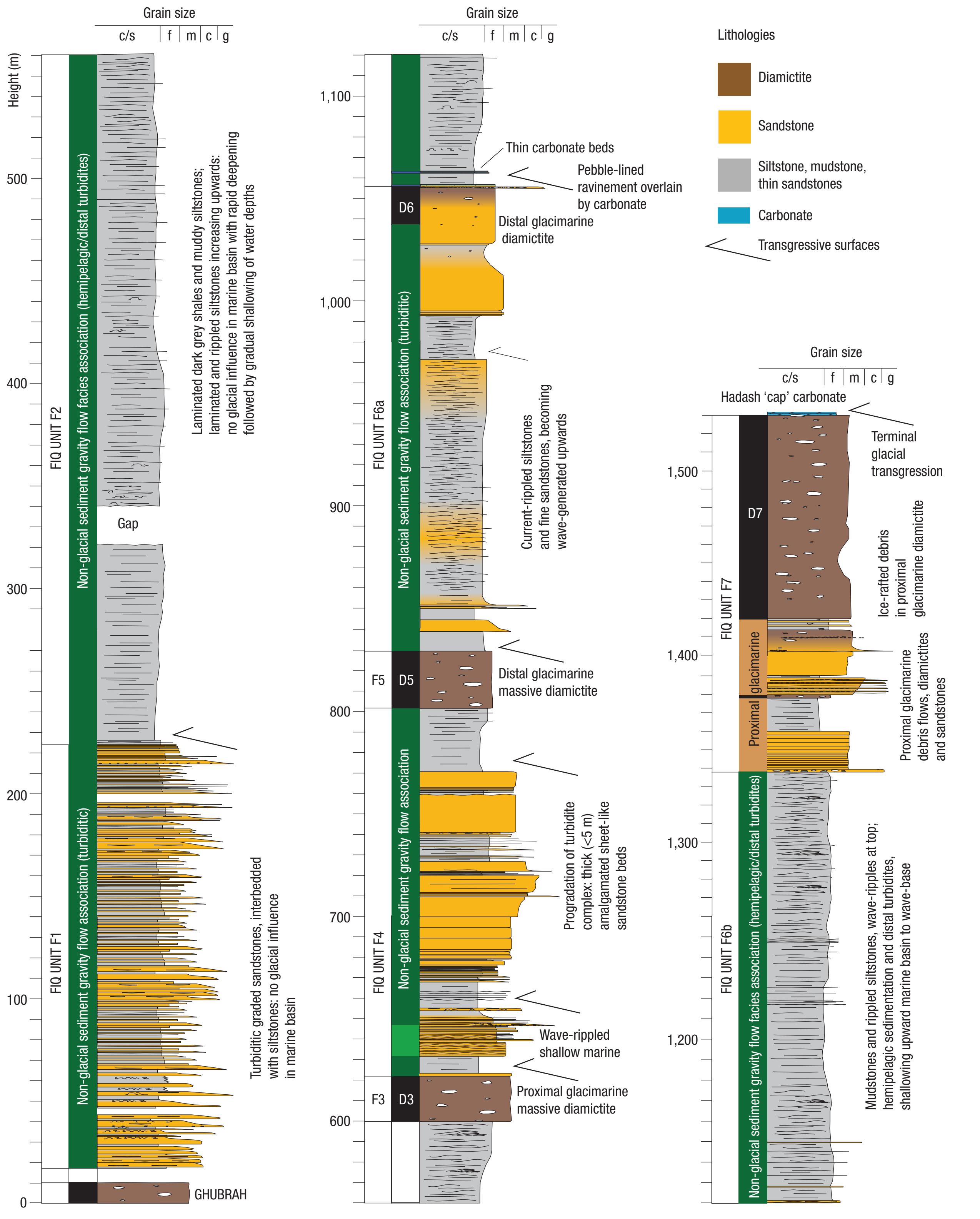

Figure 2 Record of the 1.5-km-thick sedimentary succession of the Fiq Formation close to the village of Dabu't in Wadi Sahtan, al Jabal Akhdar, Oman (data used are from ref. 100). The bulk of sedimentary rocks recorded were deposited as coarse and fine-grained sediment gravity flows and shallow marine wave-rippled sandstones, without any recognizable glacial influence. These sedimentary units are interleaved with glacimarine diamictites formed by rain-out from floating ice and sediments deposited by mobilization from a grounded ice front. Stratigraphic units are delimited by surfaces representing rapid deepening of palaeowater depth (transgressive surfaces). Commonly, glacimarine diamictites are overlain by pebbly lags formed by transgression and thin carbonate beds or cementation zones. The thickest carbonate, however, is the Hadash 'cap' carbonate. Nomenclature follows refs 42 and 100. The Fiq Formation is divided into 7 units that can be correlated across the basin. D3, D5, D6 and D7 refer to the diamictites found in units 3, 5, 6 and 7. For the different grain sizes: c/s is clay/silt, f is fine sand, m is medium sand, c is coarse sand and g is granules.

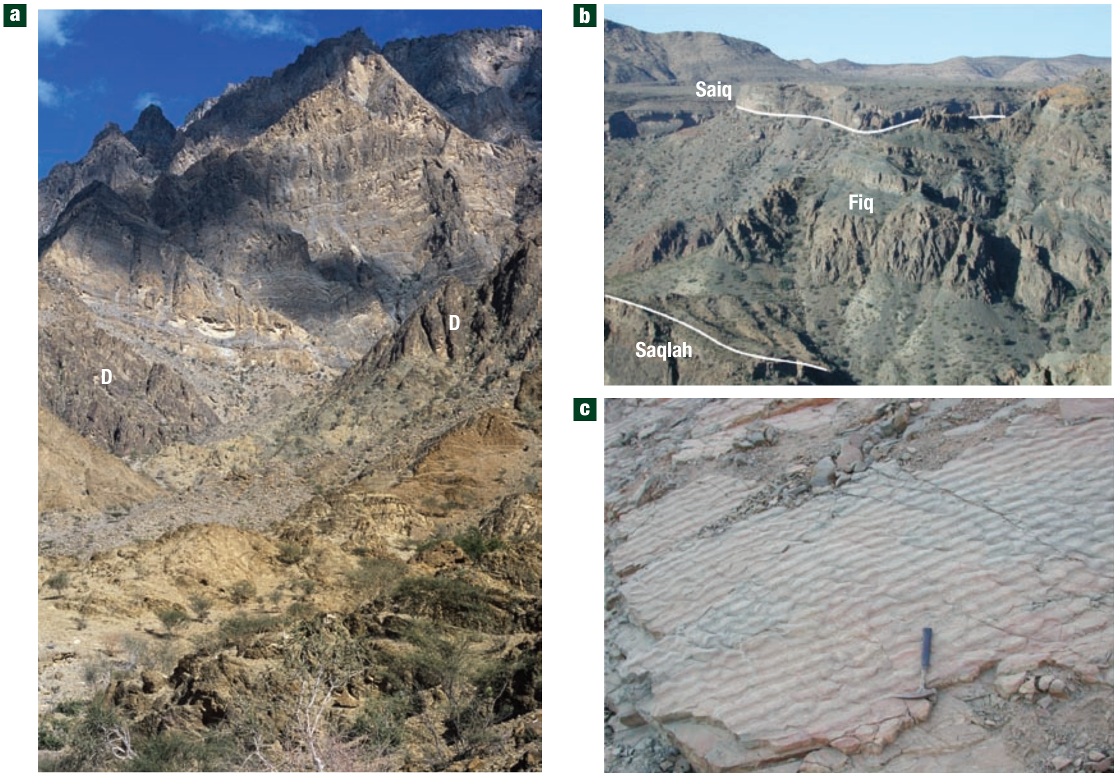

Figure 3 Glacial and non-glacial sedimentary rocks of the Fiq Formation in the Jabal Akhdar of northern Oman. **a**, Thick Fiq succession in Wadi Mistal showing multiple diamictites (dark brown cliffs, D) embedded in approximately 1 km of stratigraphy, beneath the cliff-forming carbonates of the Permian to Mesozoic. **b**, The Fiq Formation overlies volcanics and volcaniclastics of the Saqlah unit, and is erosionally truncated by the Permian Saiq, Wadi Mu'aydin. The steep brown cliffs of diamictite are embedded in non-glacial grey shales and sandstones. Several cycles representing glacial advance and retreat are evident. **c**, Bedding plane covered in wave ripple marks due to agitation of the seabed by surface gravity waves acting on an open water surface, Wadi Sahtan. No ice was present at the time of deposition of structures such as these.

To add to these difficulties, glacially transported sediment is commonly remobilized by gravity to form mass flow deposits. Consequently, glacially influenced sedimentary successions often consist of a mixture of unambiguous debrites, beds rich in isolated striated (scratched) and faceted stones attributed to glacial transport, and a range of deposits between these two extremes[42,43].

The value of sedimentary data to the Snowball Earth debate is that they provide insight into the processes and environments of deposition during Neoproterozoic glacial periods, with the stratigraphic packaging showing how the entire succession was built up over time. Some sediment types and structures are particularly informative. For example, a common component of Cryogenian successions is the fine-grained, muddy (commonly laminated) marine sediment that accumulated slowly on the sea bed, containing dispersed sand- to cobble-sized clasts (known as dropstones) that pierce the underlying laminations and are draped by the overlying laminations. These dropstone-rich, or glacial rainout[44] intervals alternate with laminated mudstones lacking dropstones, strongly suggesting the episodic influence of ice rafting or the advance–retreat of glacier-fed ice shelves from a fluctuating ice margin. Rarely, bedding surfaces are found with grooves and striations, providing conclusive evidence of ice movement (Fig. 1d). Ice wedge features identical to those forming in present-day periglacial environments are common in Neoproterozoic successions from as far afield as Mauritania, Scotland, Spitzbergen, Norway and Greenland, and are classically displayed in sedimentary rocks of the Stuart Shelf of South Australia[45].

The existence of grounded glacier ice in the Neoproterozoic Port Askaig Formation, Scotland, is supported by the presence of two distinctive units (Great Breccia and Disrupted Beds) containing extensive intraformational deformation structures[46,47]. Although some workers regard this deformation as resulting from slope failure and mass movements down submarine slopes[40,48,49], other interpretations involve a glacitectonic origin[47,50], most likely in a proglacial thrust–moraine complex and in subglacial settings under grounded ice. Mineralogical and chemical indices from fine-grained sediment in the Huqf Supergroup of Oman and the Yangtze Platform of south China suggest changes in the intensity of chemical weathering on contemporary land surfaces that correlate with glacial (low chemical weathering) and inter- or non-glacial (high chemical weathering) conditions, which indicate a dynamic climatic state[51–53].

Large volumes of sediment were supplied from ice streams and outlet glaciers into the ocean over extended periods of time during the Neoproterozoic. Sedimentary successions typically show an interbedding of glacially derived diamictites with other non-glacial rock types in thick kilometre-scale stratigraphic intervals[42,43,54–56]. Non-glacial sediment types include packages of thick-bedded (>1 m) turbidites, produced by deposition from sediment-laden gravity flows that moved down submarine slopes. Such alternation of glacially influenced intervals and thick turbiditic sandstones throughout the sedimentary succession points to vigorously operating sediment routing systems[44,55,56], as one would expect of a glaciated continental basin margin.

Extensive, thick prisms of sediment are known to have been deposited over the past ~15 million years at the edge of the Antarctic ice sheet[57]. The Antarctic geological drilling programme (ANDRILL) recently recovered 1,285 m of sediment core from a location in the

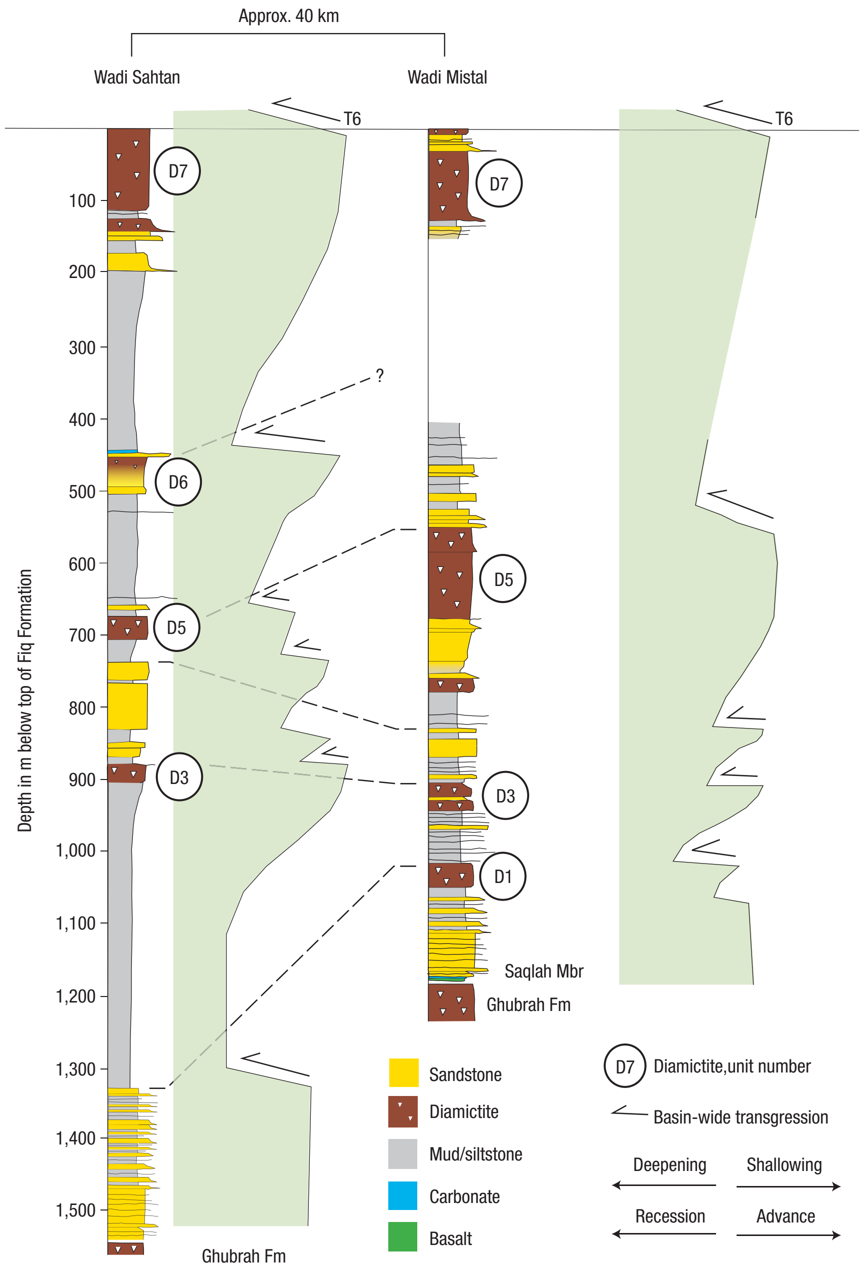

Figure 4 Correlation of two sedimentary profiles, 40 km apart, measured in the Fiq Formation of the Jabal Akhdar region of northern Oman, showing interleaving of glacial marine diamictites and non-glacial sedimentary rock types[42]. Diamictites D3, D5 and D7 are recognizable basin-wide, whereas others are confined to one or the other basin margin. The entire basin-fill accumulated during the operation of active sediment routing systems sourced from each basin margin. Cycles of water depth variation are interpreted to reflect relative sea level changes driven by ice growth and recession.

Ross Sea area. Analysis of the core shows clear evidence of repeated advance and retreat of the ice sheet, with diamictites deposited during glacial advances, and fine-grained clays and siliceous deposits forming during recession, when sea levels rose and coarse-grained sediment supply from the ice sheet failed to reach the drilling site. The sediment types and their vertical arrangement are highly reminiscent of those of the Neoproterozoic. Indeed, up to 17 glacial advance–retreat cycles were interpreted in the Neoproterozoic Port Askaig Formation in the Garvellach Islands of Scotland[46].

Although this does not mean that the deposits of the Antarctic margin are perfect analogues for the glacial stratigraphy of the Cryogenian, the entire assemblage of siliciclastic sediments deposited during the glacial periods of the Cryogenian can be explained satisfactorily by reference to modern and geologically young examples[43,58]. In this sense, there is nothing 'unusual' about Cryogenian glacial stratigraphy.

THE FIQ FORMATION OF OMAN

The <1.5-km-thick Fiq Formation of the Huqf Supergroup in Oman provides important additional evidence of the nature of glaciation during the Neoproterozoic[42,43,59]. Although the age of the Fiq Formation

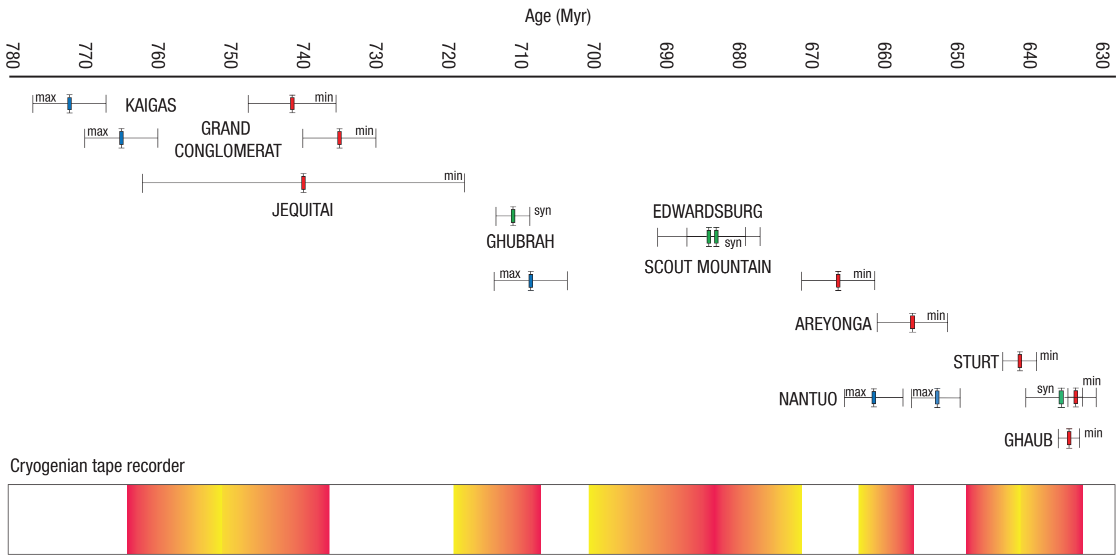

Figure 5 Radiometric age constraints on Cryogenian glaciations based on data in Table 1. Key maximum (max), minimum (min) and syn-depositional (syn) ages are indicated for relatively well-constrained glacially influenced successions. The 'Cryogenian tape recorder' shows the most plausible but non-unique distribution of ice ages based on these radiometric dates. Note that dates obtained from different radio-isotopic methods are of variable precision.

is not known precisely, it contains reworked and transported zircon crystals near its top that are as young as 645 Myr ago (ref. 60), indicating that it is a late Cryogenian deposit. Glacially influenced sediment types are embedded in non- or inter-glacial stratigraphy at many levels, indicating that glacial processes alternated with ice-free conditions throughout the deposition of the Fiq Formation (Fig. 2). Sedimentary rocks showing the influence of glacial activity include marine diamictite units (from a few metres to 100 m thick) (Fig. 3a,b) commonly containing striated and faceted pebbles dispersed in a sandy and silty matrix, as well as laminated mudstones and siltstones punctured by small pebbles that have clearly been dropped from floating ice at the same time as dilute turbiditic underflows periodically swept the sea bed close to a grounded ice margin.

These glacially influenced sediment types are interbedded with sediments that show no direct glacial influence (Fig. 1a,b). These include conglomerates, pebbly sandstones and pebbly mudstones generated by gravitational flow of debris down submarine slopes; sandstones deposited by turbulent seabed-hugging currents; mudstones deposited from turbid plumes issuing from the ice front; and wave-rippled sandstones deposited on the sea-bed within reach of surface wind-generated waves (Fig. 3c). The symmetrical, commonly trochoidal, profiles and linear crestlines in planform view of the ripple-marks distinguishes them as generated by wave action, requiring an open water body and relatively shallow water depths[61]. Abundant wave-generated ripple-marks occur in other glacial successions such as the Elatina Formation[62,63]. There was clearly no ice cover at such times. As wave periods are critically dependent on fetch[61], the wave ripple-marks of the Fiq require open water bodies much larger than an isolated 'pool' or 'oasis'.

Correlation of the distinctive diamictite units across the outcrop area in the Jabal Akhdar of northern Oman (Fig. 4) shows that some of them are local, preserved close to the basin margin, whereas others can be correlated entirely across the approximately 50-km-wide basin, demonstrating widespread deposition from icebergs and floating ice sheets. The thickest basin-wide diamictite is the youngest, and it is directly overlain by carbonates, presumably deposited during deglaciation. Evidently, throughout the glacial epoch, glaciers advanced and receded, followed by major marine transgression. At other localities, such as in the Mirbat area of southern Oman[64,65], glaciers retreated up valleys leaving terrestrial outwash plains and deltas (Fig. 1a,b) before readvancing. A similar picture of repeated glaciations, causing glacially influenced diamictites to be encased in non-glacial stratigraphy, is found in other Neoproterozoic successions in widely scattered localities on several continents[46,49,66–68].

DYNAMIC GLACIATION AND THE HYDROLOGICAL CYCLE

The apparent contradiction between the sedimentological evidence for an active hydrological cycle[42,44,54-56,58] and the requirements of global glaciation in the Snowball Earth concept has been investigated by modelling ice sheet growth during the early build-up stage of a Snowball cycle[22]. In model runs, some wet-based, dynamic ice sheets—potentially important in promoting ice flow and thereby sediment efflux to the ocean[69]—were simulated on a continental reconstruction for the early Cryogenian (760–700 Myr ago). However, the dynamic glaciation simulated does not explain an active hydrological cycle driving high sediment discharges into open water during the full duration of a Snowball cycle. Critical evidence is therefore required as to whether deposition of sediments took place in the early build-up phase, during recession or essentially occurred continuously during a glacial cycle.

In the well-dated Ghaub glacial succession of Namibia, which terminated at approximately 635 Myr ago (ref. 70), an erosive trough is thought to have been carved by an ice stream at the glacial maximum, followed by the deposition of a thick (<600 m) morainic ridge entirely during recession[71]. Such thick ridges of moraine can accumulate quickly (<10^5 years) by analogy with Pleistocene examples[72]. This allows for Ghaub sediments to be deposited in an active hydrological regime in open water, but it does not prove that the oceans were previously completely covered with ice. Nor does the idea of rapid accumulation entirely during recession explain the great thicknesses of interbedded glacial and non-glacial stratigraphy typical of many Neoproterozoic successions[46,49,66–68].

It raises an interesting secondary problem that deposition of the cap carbonate would need to be delayed until a precise moment towards the end of a long recession, instead of abruptly during a

Table 1 Geochronological data used to construct Fig. 5, showing the distribution of glacial epochs over the interval from approximately 780–630 Myr ago. Geochronological data are selected that best constrain the beginning and end of glaciation, but comparison of dates is problematic because of the different methods used (see text). Poorly constrained glacial deposits are not included.

Stratigraphic unit from Fig. 5	Maximum age (Myr ago)	Minimum age (Myr ago)	Key references
Kaigas Formation, Namibia	771 ± 6 Myr, Granite of Richtersveld Igneous Complex, $^{238}U–^{206}Pb$ zircon	741 ± 6 Myr, Rosh Pinah Rhyolite $^{207}Pb–^{206}Pb$ zircon	101, 102, 103
Grand Conglomerat, Kundelungu Basin, Zambia	763 ± 6 and 765 ± 5 Myr, Mwashia Group lavas, SHRIMP $^{238}U–^{206}Pb$ zircon	735 ± 5 Myr (syndepositional), altered volcanic pods in contact with glacial strata, SHRIMP $^{238}U–^{206}Pb$ zircon	104
Jequitai Formation, Brazil	900 Myr, detrital zircons in Jequitai Formation, $^{238}U–^{206}Pb$ zircon	740 ± 22 Myr, cap carbonate of Bambui Group, $^{207}Pb–^{206}Pb$	105, 106
Ghubrah Formation, Huqf Supergroup, Oman	723 + 16/-10 Myr, 713.7 ± 0.5 Myr, syndepositional tuffaceous ash near top of Ghubrah Formation, $^{238}U–^{206}Pb$ zircon		59, 60, 107
Edwardsburg Formation, Idaho, USA	685 ± 7, 684 ± 4 Myr, volcanic rocks interbedded with glacigenic facies of first Windermere Group glaciation, SHRIMP $^{238}U–^{206}Pb$ zircon		108
Scout Mountain Member, Pocatello Formation, Idaho, USA	709 ± 5 Myr epiclastic tuff breccia immediately below Scout Mountain Member, SHRIMP $^{238}U–^{206}Pb$ zircon	667 ± 5 Myr, reworked air-fall tuff 20 m above uppermost diamictite and cap carbonate, SHRIMP $^{238}U–^{206}Pb$	109
Areyonga Formation, Amadeus Basin, Australia	897 ± 9 Myr, Stuart Dyke Swarm, $^{87}Rb–^{87}Sr$	657.2 ± 5.4 Myr, immediately postglacial basal Aralka black shales $^{187}Re–^{187}Os$	86
Sturt Diamictite, Adelaide Rift Complex, Australia	777 ± 7 Myr, Boucat Volcanics >6 km below Sturtian glacial deposits, $^{238}U–^{206}Pb$ zircon	643.0 ± 2.4 Myr, immediately postglacial black shale of Tindelpina Shale Member, $^{187}Re–^{187}Os$	86
Nantuo Formation, south China	663 ± 4 Myr, tuffaceous bed in basal Datangpo, $^{238}U–^{206}Pb$ zircon: 654.5 ± 3.8 Myr, ash immediately below Nantuo glacial deposits, ion microprobe (SHRIMP) $^{238}U–^{206}Pb$ zircon	635.4 ± 1.3 and 632.4 ± 1.3 Myr $^{207}Pb–^{206}Pb$: 635.23 ± 0.57 and 632.5 ± 0.48 $^{238}U–^{206}Pb$, volcanic ashes in cap above Nantuo	77, 87, 110
	636.3 ± 4.9 Myr, fallout tuff 4.8 m above base of Nantuo, ion microprobe (SHRIMP) $^{238}U–^{206}Pb$ zircon		77
Ghaub Formation, Namibia	635.5 ± 1.2 Myr, syndepositional ash in uppermost Ghaub Formation 30 m below Keilberg cap, $^{238}U–^{206}Pb$ zircon		70

highly contracted, catastrophic meltback (a few thousand years), as proposed in the Snowball Earth concept. A prolongation of the period of carbonate deposition during deglaciation (one or two million years) has been proposed independently using correlation of carbon isotopic profiles[73], geochemical arguments[74] and on the basis of the occurrence of several magnetic reversals within the 'cap' carbonate[75,76]. A lag before carbonate deposition is also suggested by the presence of a fine-grained boundary claystone above the Nantuo glacial sedimentary rocks but below the cap carbonate of the Doushantuo Formation in south China[77].

It is implausible that the cyclical, 1.5-km-thick Fiq Formation, and other similar glacial successions, were deposited only during catastrophic melting of a previous global glaciation. The most likely explanation is also the most obvious: the entire glacial epoch, for however long it lasted, was climatically pulsed, just as in the Phanerozoic examples of ice ages[78] that we are very familiar with — including the late Cenozoic era, typified by Antarctica. It is often stated that Antarctica provides an analogue for glacial processes in the Snowball events of the Cryogenian. We would slant this differently: Antarctica does indeed provide an analogue, but of sedimentation along ice-margins in a partially glaciated world, not a Snowball-type glaciation.

HOW MANY GLACIATIONS AND WHEN?

If a fundamental keystone of the Snowball Earth concept is the previous existence of a small number of prolonged, global glaciations, then the supposed global correlation of glacial deposits and the distinctive carbonates that directly overlie them takes on some importance. Geochronology is vital in the evaluation of such a global correlation. However, the interpretation of radiometric dates is complicated by the variety of methods used[60]. For example, some high-resolution methods using the U–Pb system in zircons minimize the possibility of Pb loss (which causes slight age discordance) by chemical abrasion prior to isotope dilution thermal ionization mass spectrometry (ID–TIMS). Dates using this method cannot be compared in a straightforward way with U–Pb dates obtained using other, lower-resolution but more rapid techniques, such as laser ablation and ion microprobe. A combination of analytical imprecision and the inability to detect Pb loss means that dates obtained using lower-resolution methods are commonly younger than the true zircon crystallization age. Improvements over time in geochronological methods and the wide variety of techniques used has resulted in a complex historical mixture of dates that cannot be easily deconstructed, making Neoproterozoic correlation problematic.

Early ideas of Neoproterozoic glaciation promoted what might be called the two-epoch paradigm, named from localities in Australia where Cryogenian glacial deposits have been identified: the 'Sturtian' and 'Marinoan' (refs 79,80). A third, Ediacaran-aged, younger glaciation is known as 'Gaskiers' or 'Varangerian' (refs 81–83). This paradigm relied not on radiometric dates, but on the correlation of the negative excursions in the $^{13}C/^{12}C$ ratio in bulk carbonate found both below and (especially) above the glacial deposits[84], which were assumed to be globally isochronous markers. Subsequent to the Sturtian and Marinoan glaciations being proposed as the two Snowball events of the Neoproterozoic, a very large number of radiometric dates have been published, principally from U–Pb dating of zircons, and latterly through Re–Os dating of black shales[85,86]. The result is that the semblance of two discrete isochronous glacial epochs has dissolved into a picture of many glaciations over the period from 780–580 Myr ago (ref. 43) (Fig. 5 and Table 1)—although some of this variation may be due to the different isotopic methods used.

Some of these glacial deposits are undoubtedly widely correlatable; for example the often-quoted Ghaub Formation equivalents of northern Namibia and the Nantuo Formation deposits of south China, which both indicate glacial termination close to 635 Myr ago[70,87]. This is hardly surprising as the Last Glacial Maximum of the Pleistocene also terminated at the same time in both hemispheres[88]. The presence of (partial) synchrony therefore gives no information on the occurrence of a global, prolonged freeze, whereas the presence of multiple glaciations over the period 780–580 Myr ago, should they be confirmed as more dates become available, is highly damaging to the Snowball Earth concept.

Global correlations of carbon isotopic spikes, justified by the assumption that they unambiguously reflect the composition of Precambrian sea water from which the carbonate was precipitated, are also questioned[17,89–92] and a meteoric diagenetic, organogenic or methanogenic origin cannot be discounted. The widespread similarity of the sedimentary and isotopic characteristics of cap carbonates is one of the most compelling arguments for a global or near-global oceanographic response to deglaciation and has been termed the smoking gun of Snowball glaciation[3]. This looks somewhat more uncertain in the light of recent results.

ALTERNATIVES TO SNOWBALL EARTH

In summary, the sedimentological and stratigraphic data suggest that although ice probably formed in low latitudes, some of the Earth's oceans remained essentially ice-free and permitted free exchange with the atmosphere, and that the water cycle acted vigorously and normally throughout glacial epochs.

The Neoproterozoic icehouse was probably characterized by a rather large (not yet fully known) number of glacial advances, separated by interglacial periods. In some glaciations, ice occupied low latitudes. Large seasonal variations of temperature at low latitude are indicated by well-preserved periglacial ice wedges[45]. During deglaciation, especially at the end of the Cryogenian, distinctive carbonate rocks were deposited diachronously as sea levels rose from the exceptionally low levels during the last gasp of the glacial period[71]. Estimates of the magnitude of sea level change caused by the melting of land-based ice range up to 0.5 km (ref. 73).

The duration of carbonate deposition accompanying deglaciation was long enough to record the reversal of the Earth's magnetic field several times[6–9,93]. Winds were strong and sustained during the climatic transit[94]. The coastal oceans may have been covered by an extensive freshwater lens from the pouring in of meltwater and run-off from increased precipitation[95]. Glaciation on Earth never recurred with the intensity of the Cryogenian, but the presence of glacial deposits and landforms at low latitude in the Permo-Carboniferous period of North America suggests that tropical glaciation at sea level may not be unique to the Cryogenian[96].

The Neoproterozoic Icehouse had many of the characteristics of other Phanerozoic icehouse periods, but on an Earth with a fundamentally different biosphere (specifically lacking calcifying plankton and biomineralization by metazoa[97]) and with a reduced solar luminosity. This evidently led to glaciation, at least locally at low latitude. Whether ice was nucleated on topographic highs associated with active tectonics[12] is not conclusively known, but climate models using topographic effects demonstrate its potential importance in focusing precipitation and sourcing glaciers[23,98].

There are two states of the Earth system that would accommodate the sedimentological data presented above: one involving a high planetary obliquity during the Cryogenian, causing coldness and extreme seasonality in low latitudes[14], and another in which ice advance stalled despite the anticipated runaway ice–albedo effect, leaving ice-free tropical oceans[28], without the requirement of a fully glaciated planet.

If the ice advance was stalled, it is an intriguing research question of what led to the Earth's escape from global glaciation. The answer may lie in the link between the physical climate system and the carbon cycle[28]. As surface temperatures declined, atmospheric oxygen may have been drawn into the ocean, where it could have remineralized a vast reservoir of dissolved organic carbon[99], which in turn caused atmospheric CO_2 levels to build up. The resulting greenhouse could have stalled ice advance and resulted in recession, with or without the positive feedback of warming on the destabilization of methane ice[92]. If this scenario is correct, the Earth may have avoided "death enveloping all nature in a shroud", as Louis Agassiz wrote, by the unusual workings of the Neoproterozoic carbon cycle. In the climate change game, the carbon cycle is both saint and sinner.

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