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Earth-Science Reviews 65 (2004) 1–73

www.elsevier.com/locate/earscirev

'Zipper-rift': a tectonic model for Neoproterozoic glaciations during the breakup of Rodinia after 750 Ma

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Received 9 October 2002; accepted 28 May 2003

Abstract

The 'Snowball Earth' model of Hoffman et al. [Science 281 (1998) 1342] has stimulated renewed interest in the causes of glaciation in Earth history and the sedimentary, stratigraphic and geochemical response. The model invokes catastrophic global Neoproterozoic refrigerations when oceans froze, ice sheets covered the tropics and global temperatures plummeted to − 50 °C. Each event is argued to be recorded by tillites and have lasted up to 10 million years. Planetary biological activity was arrested only to resume in the aftermath of abrupt and brutal volcanically generated 'greenhouse' deglaciations when global temperatures reached + 50 °C. The 'Cambrian explosion' is regarded by some as a consequence of post-Snowball glacioeustatic flooding of continental shelves. We shall show by a systematic review of the model that it is based on many long standing assumptions of the character and origin of the Neoproterozoic glacial record, in particular, 'tillites', that are no longer valid.

This paper focusses on the sedimentological and stratigraphic evidence for glaciation in the light of current knowledge of glacial depositional systems. By integrating this analysis with recent understanding of the tectonic setting of Neoproterozoic sedimentary basins, an alternative 'Zipper-rift' hypothesis for Neoproterozoic glaciations is developed. The 'Zipper-rift' model emphasises the strong linkage between the first-order reorganisation of the Earth's surface created by diachronous rifting of the supercontinent Rodinia, the climatic effects of uplifted rift flanks and the resulting sedimentary record deposited in newly formed rift basins.

Initial fragmentation of Rodinia commenced after about 750 Ma (when the paleo-Pacific Ocean started to form along the western margin of Laurentia) and culminated sometime after 610 Ma (with the opening of the paleo-Atlantic Ocean on the eastern margin of Laurentia). Breakup is recorded by well-defined 'tectonostratigraphic' successions that were deposited in marine rift basins. The base of each succession is characterised by coarse-grained synrift strata consisting of mass flow diamictites and conglomerates (many of the 'tillites' of the older literature). These facies are interbedded with large olistostromes and contain clastic carbonate debris derived from landsliding of fault scarps along rifted carbonate platforms. Diamictites and conglomerates are dominantly the product of subaqueous mass flow and mixing of coarse and fine sediment populations (the term *mixtite* has been used in the past). These facies are not uniquely glacial and are produced regardless of climate and latitude. Synrift deposits commonly pass up into thick slope turbidites recording enhanced subsidence and are capped by uppermost shallow marine strata that record a reduction in subsidence rates and overall basin shallowing.

Tectonostratigraphic 'cycles' can attain thicknesses of several kilometres, but have been commonly misinterpreted as recording globally synchronous 'glacioeustatic', falls and rises in sea level. In fact, eustatic sea-level changes in rift basins are

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0012-8252/$ - see front matter
doi:10.1016/S0012-8252(03)00080-1

suppressed as a result of a strong tectonic control on relative water depths. The great length of newly formed rifted margins around the long perimeter of Laurentia (< 20,000 km) ensured that deposition of tectonostratigraphic successions occurred diachronously as in the manner of a zipper between approximately 740 and 610 Ma. Some successions show a definite glacial influence on sedimentation as a consequence of latitude or strong tectonic uplift, but many do not. Regardless, all deposits record a fully functioning hydrological cycle entirely at odds with a supposed fully permafrozen planet.

Mapping of those deposits where a definite glacial imprint is apparent indicates that Neoproterozoic glaciation(s) were likely regional or hemispheric in scope and latitudinally constrained. They were perhaps no more severe than other glaciations recorded in Earth history. The regional distribution of ice centres is argued to have been influenced by tectonic topography created by large mantle plumes and by rift shoulder uplift. Paleomagnetic data indicative of tropical glaciation are, in our view, ambiguous because of uncertainty as to *when* such paleomagnetic characteristics were acquired. A lower solar luminosity may have played a role in lowering snow line elevations and displacing glaciation into latitudes lower than those of Phanerozoic glaciations. Global tectonic and volcanic activity, especially the rapid burial or organic carbon in new rift basins, may explain extreme shifts in C-isotopic values evident in late Neoproterozoic strata.

Keywords: Neoproterozoic; ‘Zipper-rift’; Snowball Earth; Rodinia; Rifting; Tectonic topography; Glaciation

1. Introduction

Poorly sorted Neoproterozoic diamictites, inferred by many geologists to be direct sedimentary products of large continental ice sheets (*tillites*), are found on all continents and were deposited between approximately 750 and 610 Ma. In the absence of site-specific age data on key stratigraphic horizons, Neoproterozoic diamictites are still viewed by many as precise age-correlative marker horizons recording globally synchronous changes in climate and eustatic sea level. More recently, it has been argued, in conjunction with rapid changes in ^{13}C and ^{87}Sr/^{86}Sr ratios, that the planet was repeatedly and entirely ice-bound for many million years when nearly all organic activity ceased and oceans froze to depths of 1 km or more under global temperatures of -50 °C (the “Snowball Earth”).

Evidence for the Snowball Earth model focusses on geochemical and geophysical (paleomagnetic) data along with the presence of so-called ‘cap carbonates’ argued to record rapid global deglaciation. In contrast, the tectonic setting, sedimentology and depositional environment of supposed glacial deposits have been largely ignored by proponents of the Snowball model.

Our intent here is to refocus debate regarding Neproterozoic climates on the sedimentologic and stratigraphic record of glaciation. By scrutinizing this record in the light of recently gained knowledge of glacial depositional systems and by combining such data with information regarding Neoproterozoic tectonic settings, a new model for Neoproterozoic glaciations is proposed. We argue that Neoproterozoic glaciations were regional in extent and probably no different in character and thermal regime from those of the Phanerozoic. Mapping of glacial strata across Rodinia indicates that a key factor allowing the growth of ice covers may have been extensive uplift of rift shoulders and plateaux in mid-to-high latitudes during the protracted rifting of the supercontinent Rodinia. Rifting began after 750 Ma as Laurentia progressively ‘unzipped’ from Rodinia to form the paleo-Pacific Ocean. A second phase of rifting and glaciation occurs at about 610 Ma when Baltica broke away from the eastern margin of Laurentia to form the Iapetus Ocean (paleo-Atlantic).

2. The paradox of Neoproterozoic climate; catastrophic change or business as usual?

Neoproterozoic successions containing diamictite facies, often of great thickness, occur on every continent. Currently, this record is interpreted by different groups of geoscientists *either* as a series of catastrophic changes without parallel in Earth history (Williams, 1994; Hoffman and Schrag, 2002; Hoffman et al., 1998a) and having fundamental implications for the biological evolution on the planet (“a script for global catastrophe”, Runnegar, 2000) *or* as being a record of glaciation little different from that of other glacial epochs which were controlled primarily by tectonics and geography (Eyles, 1993; Crowell, 1999; Leather et al., 2002). At the heart of the debate lie very different interpretations of the origin and paleoclimatic significance of diamictite facies.

2.1. Diamictites; glacially deposited tills, glacially influenced marine or nonglacial?

Diamictites (lithified diamicts) are poorly sorted 'concretelike' facies and are a highly conspicuous component of many Neoproterozic stratigraphic suc-

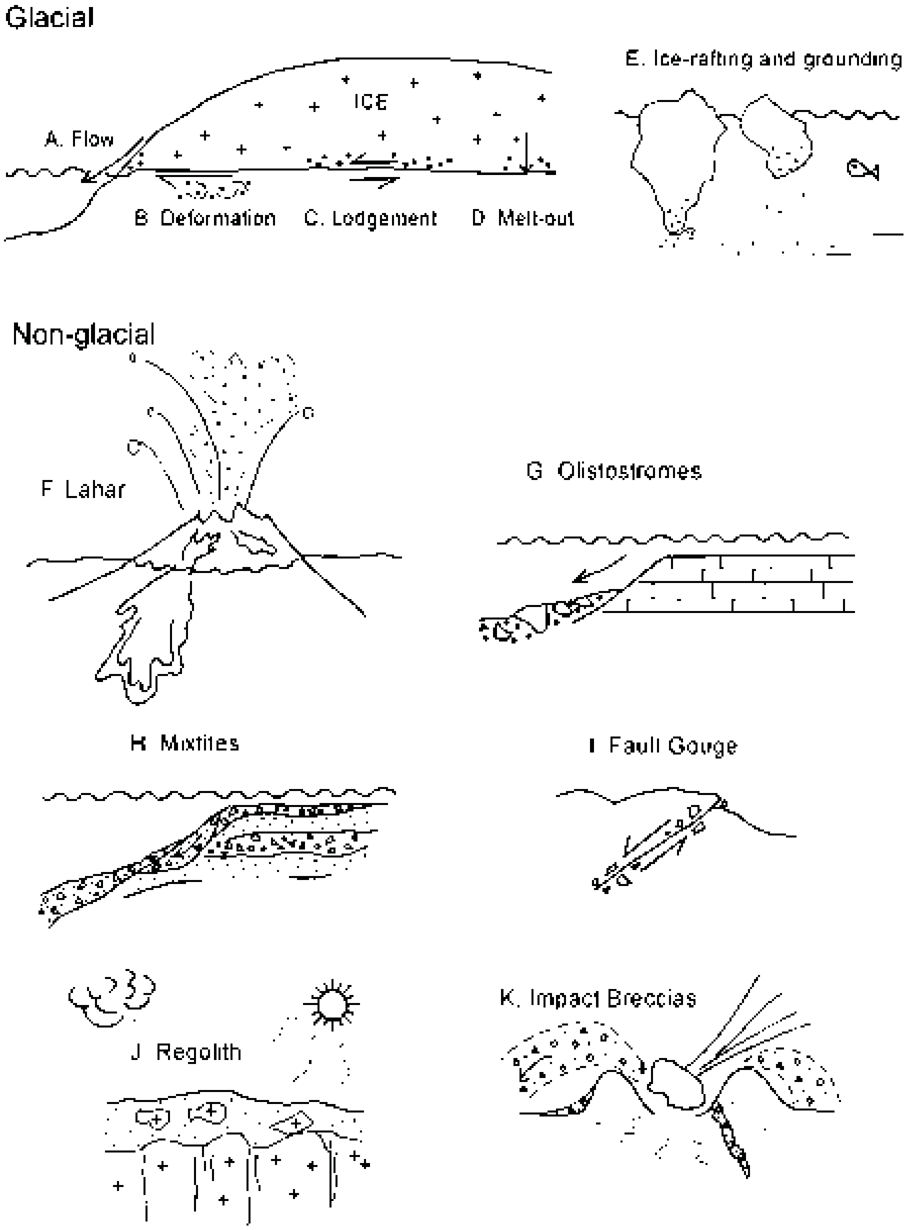


Fig. 1. Glacial and nonglacial environments in which diamict facies are produced.

cessions. They are often labelled as 'glacial' simply on the basis of their poor textural sorting and physical resemblance to the deposits left behind by modern wet-based glaciers. These glaciers slide over their beds and generate coarse-grained, poorly sorted glaciclastic sediment (*till*, *tillite*). Unfortunately, despite their till-like appearance, diamictite facies are not uniquely glacial in origin, but are produced on planet Earth in a very wide range of depositional settings regardless of latitude or climate (Fig. 1). Some are generated as tills, some as glacially influenced marine deposits where ice margins release debris that flows downslope or where icebergs drop debris into ocean floor muds. Most, however, are generated by mass flow (debris flows) on unstable slopes in tectonically active areas such as in rift basins and subduction zones, on continental slopes and on the margins of volcanoes and reefs (Einsele, 2000). Clearly, our understanding of the functioning of the Neoproterozoic climate system and even biological evolution is reliant *on the correct paleoenvironmental interpretation of diamictite facies*.

Many proponents of extreme Neoproterozoic climate change entertain a simple view of the origin of diamictites; they are glacial, were deposited in the same geologic instant and thus their worldwide distribution implies the presence of enormous ice sheets covering the tropics, the like of which never subsequently formed on Planet Earth (Hoffman, 2002). In the absence of good dating control, deposits inferred to be glacial are simply regarded as time correlative.

2.2. Structure of this paper

In **Part I** of this paper, we review the historical development of ideas on global glaciation and attendant progress in the description and interpretation of ancient glacial deposits. We then systematically examine 10 fundamental assumptions on which the 'Snowball' model is based. We pay particular attention to biological, isotopic and sedimentologic evidence for global terrestrial ice sheets, the paleomagnetic data held to support cold climates at the tropics and the presence of 'capping carbonates' associated with some diamictites and held to record extreme changes in global climate. We shall show that the model is rooted in several long-held ideas regarding the origin and climatic significance of Neoproterozoic diamictites and associated facies that are no longer compatible with modern knowledge of glacial depositional systems.

In **Part II** of this paper, we review the global sedimentologic and stratigraphic record of Neoproterozoic glaciation in the light of modern understanding of depositional processes and plate tectonics. Many Neoproterozoic diamictites that the Snowball Earth model assumes to be glacial are submarine mass flows triggered by active faulting and landsliding in rift basins and have no climatic significance. Deposits indicate a fully functioning hydrological cycle at the time of deposition.

Finally, in **Part III**, we present a tectonostratigraphic model for Neoproterozoic diamictites which we call 'Zipper-rift', emphasising the tight coupling of glaciation and uplift accompanying the protracted breakup of Rodinia after 750 Ma.

3. Part I: Global glaciation—from die eiszeit to the snowball

3.1. The history of a hypothesis

Few ideas have gripped people's imaginations such as that of the nightmare scenario of a completely icebound Earth, where life is arrested and even extinguished by extreme cold. The theme appears in Norse creation myths and in other northern cultures, reflecting a universal creation motif where a divine creator is disgusted with early humanity and decides to wipe the slate clean (e.g., Leeming and Leeming, 1994). In the Norse story of Ragnarok, the world is brought to a dreadful end by the *Fimbulvinter*, a story that was already old when written down in A.D. 1220, as part of the epic poem *Edda* by the Icelander Snorris Sturluson. Other Norse creation myths tell of the evil Ice Giant *Ymir*, who is clearly based on folk memories of the last glaciation. The forensic climatologist Lamb (1978) recounted similar folk legends from Asia and Iran, where a golden age is destroyed by intense cold. Recently, the theme has been taken up by writers of science fiction. Aldiss (1985) writes in his *Helliconia* trilogy of the catastrophic nature of a global glaciation when 'cold gripped the favoured lands of the equator' and the planet 'lay in a chill catalepsy', 'wiping the Earth clear of festering civilizations'. Other iterations of the same theme are provided by Halacy (1978), writing at a time when global cooling not warming was a topic of much scientific and public discussion.

Louis Agassiz delivered the first formal scientific presentation of the notion of global glaciation in 1837; we label his hypothesis the 'first snowball'.

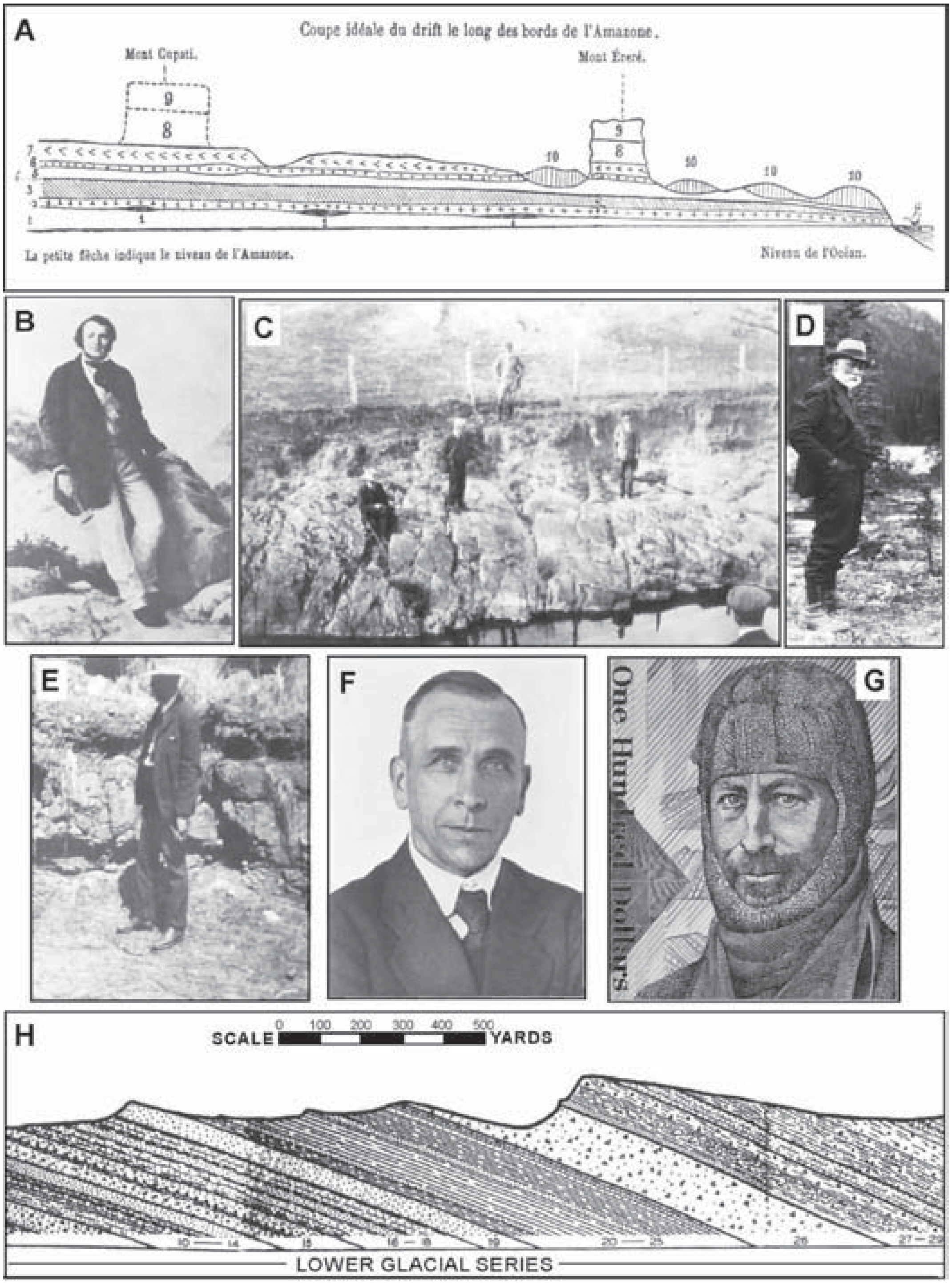
3.1.1. The first snowball (1837–1876): the Pleistocene 'eiszeit'

Louis Agassiz invoked 'die Eiszeit' (a name borrowed from his friend Karl Schimper's poem) following his famous 1837 *Discourse of Neuchatel* (Agassiz, 1840, 1842; Carozzi, 1966, 1967; Fig. 2B). He astounded his audience by arguing that an ice age had been divinely inspired and had wiped out all life ('death enveloped all nature in a shroud') severing any genetic relationship between past and present life forms. 'The development of these huge ice sheets must have led to the destruction of all organic life at the Earth's surface'. Species were generated anew after the Ice Age and glacial landforms, such as drumlins and their attendant-rich soils, were seen as the product of 'God's great plough'. Agassiz was intrigued by mammoths preserved in the Siberian permafrost as if suddenly frozen and saw them as support for his creationist and catastrophist model. The public and scientists alike were outraged at his notion that a 'Siberian winter established itself for a while on ground previously covered by rich vegetation and inhabited by great mammals'. The reaction of the audience during his lecture at Neuchatel was so unruly that some observers feared fisticuffs (Bolles, 1999, p. 87).

Driven by an unyielding belief in catastrophism and opposition to Darwin's theory of evolution, Agassiz was haunted by the notion that life may have survived an Ice Age unscathed in tropical oases. Agassiz was undeterred by the 1863 publication of Lyell's book on *The Geological Evidences of the Antiquity of Man* that had marshalled evidence of the southward migration of pre-Ice Age species, including humans, during the last Ice Age. J. Lubbock introduced the term 'prehistory' in 1865 recognising that glaciation had simply interrupted life, not wiped it out. Looking for evidence of tropical glaciation, Agassiz began to explore the Brazilian Amazon between 1865 and 1866 and discovered massive red-coloured clays with pebbles and large boulders which he called "Pleistocene Amazonian drift" (Fig. 2A). This, he proposed, was evidence 'of a series of physical events extending over the whole globe...if the geological winter existed...it must have been cosmic'. According to some, Agassiz's 1866 paper on 'Traces of Glaciers under the Tropics', delivered in Washington, DC, in which he argued for equatorial low latitude glaciation, marked a 'new and fundamental phase of the Ice-Age theory' (Agassiz and Coutinho, 1868). Agassiz pressed on and wrote of a 'geological winter' extending over the whole globe (Agassiz, 1876). He dared the scientific community to 'imagine, if you can, floating ice under the equator, such as now exists on the coasts of Greenland' (Agassiz, 1886). In hindsight, it was a complete blunder (see Carozzi, 1974). The bouldery clay 'drift' was the not the product of any tropical ice sheet, but the deep weathering of igneous rocks and exfoliation of core stones (Branner, 1893). By 1870, Agassiz's notion of a worldwide cosmic winter was moribund, but was to be resurrected once more, as knowledge of pre-Pleistocene glaciations rapidly emerged.

3.1.2. The second snowball (ca. 1926): 'Worldwide refrigeration'

The study of ancient pre-Pleistocene glacial deposits began in 1855 with A.E. Ramsay's glacial interpretation of Permian breccias in central England. Later to be proved incorrect, Ramsay's work spurred others to look for evidence of ancient glaciations. Results soon followed such as W.T. Blandford's discovery of Permo-Carboniferous glacial deposits at Talchir, India, and that by A.R.C. Selwyn at Hallet's Cove, Australia, both in 1859. Ramsay argued in an address to the British Association in 1880 that glaciation may have taken place as early as the Cambrian; here, he was indeed correct for the first Precambrian glacial rocks were discovered in 1889 by H.P. Woodward in the Flinders Ranges of Australia. Other finds quickly followed such as those in Scandinavia (Reusch, 1891). Already, the presence of late Paleozoic glacial rocks in central India was seen as the product of 'a more extensive and severe glaciation than that of the glacial period of Pleistocene times' and its explanation was seen as 'a tough nut to crack' (Geikie, 1894, p. 825). The Earth's then oldest known glacial rocks (Gowganda Formation; now known to be of Paleoproterozoic age) were reported from north-


A
Coupe idéale du drift le long des bords de l'Amazone.
Mont Cupati.
Mont Ereré.
9
8
7
6
5
4
3
2
1
10
La petite flèche indique le niveau de l'Amazone.
Niveau de l'Océan.
B
C
D
E
F
G
One Hundred Dollars
H
SCALE
0 100 200 300 400 500
YARDS
10 — 14
15
16 — 18
19
20 — 25
26
27 — 29
LOWER GLACIAL SERIES

ern Ontario, Canada (Coleman, 1907) and the term *tillite* was introduced by Albrecht Penck in 1906.

Discoveries of ancient glaciations prompted great public interest for several reasons. First, emerging ‘astronomical’ theories of glaciation (e.g., Croll, 1867) appeared to imply that glaciation was a frequent recurring feature of Earth’s climate although, in fact, the apparent rarity of ‘till rock’ in the geological record, as pointed out by Wright (1882), appeared to deny this. Second, ancient glacial strata, rare or not, revealed great changes in ancient climates when many scientists believed the Earth’s surface had simply been hotter in the distant geologic past and was ‘advancing toward an icy old age’ (Coleman, 1941, p. 7). The discovery of coal and fossil trees below glacial sediments in the Antarctic and Arctic also appeared to imply great shifts in past climates. This was of some comfort to many scientists because, as Coleman explained, the finding of old glacial deposits ‘banished this gloomy foreboding’ such that ‘mankind may proceed. . .free from the a haunting dread of an approaching extinction of the race.’ Agassiz may have been long dead, but the ghost of his *Eiszeit* still haunted many.

By the early years of the twentieth century, it was beginning to look as though Louis Agassiz may have been partly right. As the geology of the continents began to be better known, geologists realised that Permian and Precambrian glacial deposits occurred virtually on all continents and *in low latitudes*. Moreover, many striated surfaces showed that ice had moved north *away* from the tropics appearing to require ice covers that made the ice ages of the Pleistocene seem insignificant by comparison. A.P. Coleman’s influential paper of 1908 and his book *Ice Ages Recent and Ancient* in 1926 reviewed what was known of Earth’s ancient glacial record (Fig. 2D). Emphasising the extensive presence of glacial rocks at low latitudes, he declared that ‘the Permo-Carboniferous ice was the most terrible known in the world’s history’ (Coleman, 1939). In a review of Pleistocene Ice Ages, published two years after his death in 1939, Coleman (1941, p. 6) stressed that the Permo-Carboniferous glaciation ‘when ice reached the tropics. . .had the better right to be called The Ice Age’ (Fig. 2C). The geomorphologist W.M. Davis accompanied Coleman on field trips in South Africa (Fig. 2E) and was equally impressed, declaring that ‘the Permian glacial climate is one of the most remarkable problems disclosed by geology today’. He firmly rejected the pre-Wegener hypothesis of ‘an Antarctic continent of which Australia, South Africa and a part of South America were possibly but lobes’ as an explanation for Permo-Carboniferous tillites in the tropics (Davis, 1908). To Coleman, explaining why the ‘world. . .found itself in the grip of the fiercest and longest winter of the ages’ was ‘one of the most thrilling problems in all of geology’ (Coleman, 1916). Sayles (1919) reviewed

Fig. 2. Early proponents of ice bound Earths. (A) ‘Amazonian Drift’ in central Brazil (labelled Unit 10); according to Agassiz and Coutinho (1868), it was evidence of widespread Pleistocene glaciation at the tropics. Much later, it was identified as clays with core stones produced by the deep weathering of igneous rock. (B) Louis Agassiz as a young man (reproduced with permission from Imbrie and Imbrie, 1979). Agassiz’s notion of a catastrophe brought on by a vast ice age (*die Eiszeit*) owed much to poetic visions and legends. ‘Ice of the past! of an Age when Frost in its stern clasp held the lands of the south’ (K. Schimper, 1837; in North, 1943). Recurring cycles of death by extreme cold and the creation of new life in the warmed aftermath of glaciation is a recurring theme in myths of the northern latitudes. (C) Geologists, including Howchin, David and Coleman, standing on Permo-Carboniferous tillite in the Inman Valley, South Australia, August 1914. (D) A.P. Coleman in the Canadian Rockies in 1912. To Coleman, understanding the Permo-Carboniferous, when the ‘world. . .found itself in the grip of the fiercest and longest winter of the ages’ was ‘one of the most thrilling problems in all of geology’ (Coleman, 1926). (E) The geomorphologist W.M. Davis examining the Dwyka Tillite of Southern Africa on a field trip with A.P. Coleman and Albrecht Penck in August 1905. The term tillite was introduced by Penck the following year. Travelling through ‘rank jungle growth, the noon sun was very hot and yet we stood on a smoothly glaciated and striated floor. . .the tillite might well have been boulder clay by the shore of a Canadian river. . ..the contrast of the present with the past was astounding’ (Coleman, 1926, pp. 106–107). (F) Alfred L. Wegener. An early student of Earth’s glacial record, he recognised that widely scattered Permo-Carboniferous glacial deposits was key evidence of a Gondwanan ice cap that straddled the polar regions of a former supercontinent (from Reinke-Kunze, 1994; Rohrbach, 1993). He also stressed that poorly sorted sediments were produced in a wide range of environments outside glacial settings (Fig. 1). (G) Sir Douglas Mawson commemorated on an Australian bank note with (H) his field sketches of Neoproterozoic Sturtian glacial strata from the Flinders Ranges of South Australia (from Mawson, 1949). He concluded that the late Precambrian glaciation had been the most ‘severe of all in earth history’; in fact, no less than ‘the world’s greatest ice age’. ‘Glacial’ strata are conformably interbedded with ‘glaciolacustrine shales’. Recent work by Young and Gostin (1991) interpret these as a submarine slope/fan succession of debris flows and turbidites deposited in the Adelaide Rift Complex that formed during the breakup of Rodinia after 750 Ma (see Fig. 4A).

what was known of Pleistocene glaciolacustrine varves and used this model to explain the presence of banded and laminated slates commonly found with Permian and Precambrian glacials. He declared with particular reference to the Permian glacials present in the tropics of India and Africa that 'it will now be necessary to explain not only the former presence of the great ice sheet in the tropics but marked alternations of seasons too.' Any theory of glaciation, Coleman (1926, p. 282) wrote , 'must account for a worldwide refrigeration affecting all zones of both hemispheres at the same time'.

The idea of worldwide glaciation found support in the Precambrian record also. After discovering widely distributed and very thick late Precambrian tillites in southwest Africa, Gevers (1931) invoked 'globally engulfing glaciations'. He wrote 'there appear to have been glacial periods of worldwide extent'. Of course, none of the conclusions of Coleman and Gevers could have been reached without them, both firmly rejecting the then radical idea of 'continental drift'. To these 'permanentists' who believed in a static Earth where continents and oceans remained parked in neutral, the wide global scattering of glacial rocks required huge ice sheets expanding into low latitudes (Coleman, 1926, 1932, 1939). The presence of ancient glacial rocks in the steamy tropical heat of low latitudes was nothing less than 'astonishing', rousing 'incredulity among the geologists of Europe and America' (Coleman, 1926, p. 97). Here, the reader should note the significant absence of any reference to geologists of the *southern* hemisphere who, by and large, embraced notions of continental drift (e.g., DuToit, 1921). 'The dry wilting sun, glare and perspiration made the thought of an ice sheet at that very spot most incredible but alluring' (Coleman, 1926). He writes of 'being laughed at by country people while I chipped striated clasts from tillite well within the tropics not far from plantations of bananas' (Coleman, 1939, p. 450). Refusing to believe that the continents had shifted, the only other explanation was to have ice at low latitudes (Coleman, 1932). The classic example of this thinking is Brooks' (1949) reconstruction of the enormous ocean-going late Paleozoic ice sheet needed to leave glacial deposits now scattered across India, Australia, South America, southern Africa and Antarctica (later to be portrayed as an 'absurdity' by Lamb, 1978, p. 288).

3.1.2.1. Global glaciation refuted: Alfred Wegener and the great 'southern glaciation'. In a classic illustration of how scientists can sometimes draw opposing conclusions from the same data, Alfred Wegener saw the global scattering of tillites as clear evidence that continents were previously clustered *together* and had since moved apart (Wegener, 1912, 1924; Fig. 2F). The wide distribution of Permo-Carboniferous tillites across the southern continents was one of the principal planks in his reconstruction of the supercontinent Pangea and its climate belts. Despite support from the southern hemisphere where the evidence is clearest (e.g., DuToit, 1921), Wegener's message largely fell on deaf ears. His theory of 'continental drift' as an explanation for tropical tillites was regarded as 'incredible' (Coleman, 1926, p. 263), a 'fairy tale' (Willis, 1944) and 'purely fantastic' (Flint, 1957, p. 503). Ironically, these three were leading North American glacial geologists; Coleman and Willis, moreover, had been Presidents of the Geological Society of America. The objections of these influential workers is ironic because to many other geologists, Wegener's reconstruction of the southern ice sheet blanketing the polar and subpolar regions of Pangea was the most *convincing* argument for continental drift (LeGrand, 1988).

That the loudest opposition to Wegener came from leading North American glacial geologists was not surprising. First, Wegener's famous map showing the supposed arrangement of land during the Pleistocene, where the outer terminal moraines of the ice sheets in Europe and North America 'join up smoothly', was very correctly rejected. Unfortunately, the entire thesis of continental drift was also thrown out. Second, Wegener had also questioned the origin of the famous 'Squantum tillite' deposit found near Boston. The Squantum was widely regarded among the geological community as a Permo-Carboniferous glacial deposit (it met 14 out of 15 criteria for being glacial as identified by Sayles, 1914, 1919), but Wegener's reconstruction of Pangea placed the Boston area *near the equator*. He warned that not all poorly sorted rocks, such as the Squantum, were true glacial tillites and thus were unreliable indicators of past climate and continental positioning (Wegener, 1928). He argued that the Squantum was not a tillite (and this was later proven correct; Crowell, 1957; Dott, 1961; see below) and, as we now know, is of Neoproterozoic age. This was an early illustration of a problem that has crippled the proper analysis of ancient glaciations: the axiomatic interpretation of poorly sorted sediments (*diamicts*) as *tillites* and poor age-dating control (see below).

In 1932, Coleman wrote that 'enough has been noted to show that theories of drifting continents are entirely inadequate to account for known facts in regard to the greatest times of glaciation'. To the permanentists such as Coleman, glaciations were seen as 'catastrophic events in the world's history'. Cotton (1942) referred to glaciations as 'climatic accidents' and Pauly (1957) referred to 'worldwide abnormal climates'. Such events were regarded as being superimposed on static continents where deep glacial erosion and deposition of coarse bouldery sediments, such as tills, simply interrupted an otherwise orderly Davisian cycle of landscape and sediment evolution from youth to maturity. The notion that glaciation was externally generated and imposed on a largely static Earth was to later generate explanations for ice ages involving the planet passing through cometary debris and dust belts (e.g., Sheldon, 1984). As a result, ancient glaciations were seen as highly unusual events ('slow motion catastrophes'; Bolles, 1999). If this were correct, then they had chronostratigraphic value because such events could be precisely correlated from one continent to another (e.g., Chumakov, 1981). In turn, because these deposits are found on all continents and can be so precisely correlated, then truly global glaciations *must* have occurred, a circular argument that still flourishes in the modern literature (see below).

3.1.3. The third snowball (ca. 1949): 'the world's greatest ice age'

The work of Sir Douglas Mawson (1949; Fig. 2G) on the Sturtian Tillites of South Australia (which he later called 'the greatest thing of the kind recorded anywhere in the world'; Mawson, 1958) can be seen as the high water mark of the classical approach to interpretation of sedimentary strata containing poorly sorted, laminated and banded rocks. Then, the *only* depositional model available was that of continental glacial deposition where tills, glaciofluvial, glaciolacustrine and aeolian deposits record the climatically driven waxing and waning of ice sheets (Fig. 2H). Ironically, Mawson's earlier visits to Antarctica, the first as a member of Ernest Shackleton's British Antarctic Expedition of 1907–1909, had been spurred by his desire to seek 'first hand knowledge of the conditions of sedimentation during an ice age' (Mawson, 1958, p. xxvii). He was disappointed because 'the products of glacial erosion are almost entirely dumped on the floor of the surrounding ocean and thus not available for investigation' (Mawson, 1949, p. 152). He had enunciated, but missed, the guiding principle in the interpretation of Earth's glacial record: that of selective preservation of glacially influenced marine facies. That Earth's glacial record is dominantly preserved in marine strata was only to be realised in the 1980s. Inspired by reports of late Precambrian tillites from equatorial Africa and their broad distribution elsewhere, Mawson (1949) invoked a massive 'worldwide' glaciation that was the world's 'greatest. . .where glaciation is evidenced even to the equator'.

3.1.3.1. The emergence of sedimentology. The birth of sedimentology as a distinct subdiscipline in the 1950s, heralded by the introduction of the turbidite depositional model, focussed attention on the varied products of submarine mass flows. It quickly became apparent that not all poorly sorted rocks were glacial tillites deposited below glaciers on elevated continental surfaces; many were nonglacial deep marine mass flow deposits intimately interbedded with turbidites. Such rocks were a common component of nonglacial submarine fan successions. J.C. Crowell was greatly influenced by the work of P.H. Kuenen and his students on laboratory and field investigations of turbidites and sediment gravity flow deposits. Crowell (1957) showed that poorly sorted 'till-like' deposits could be produced by subaqueous slumping and mixing of many different grain sizes during downslope mass flow. He also stressed the deepwater, tectonically active depositional setting of many ancient 'glacial' deposits as evidenced by their association with turbidites within thick 'flysch' successions. He wrote in 1957 that 'some glacial episodes may have been introduced into geologic history based on the interpretation of such rocks as tillites without supporting independent evidence' (p. 993). As a result, by 1960, it was appreciated that poor textural sorting was not a sufficient diagnostic criterion for recognition of glacial strata and that diamictites are generated in a wide range of marine and terrestrial depositional environments from the tropics to the poles (e.g., Dott, 1961; Winterer, 1963).

Pettijohn (1984, p. 128) wrote that the now classic turbidite paper of Kuenen and Migliorini (1950) 'unlocked the secret' by revealing that graded, fine-grained and rhythmically laminated facies were not axiomatically 'varvites' hitherto a favourite criterion among those looking for glacial evidence (e.g, Sayles, 1914, 1919). Pettijohn (1984, p. 131) recounts the 1952 Geological Society of America field trip to the Squantum Tillite near Boston, the focus of earlier debate between Coleman and Wegener in the 1920s (see above). One of the field trip participants was John Crowell 'who had seen many of such deposits in California and had never considered any of them tillites. Indeed they were pebbly mudstones, probably products of submarine slump'. Near Squantum Head were graded slates, 'interpreted as deposits in glacial lakes. . .the case for glacial origin was suspect if not downright wrong. Imagine our dismay at seeing the Squantum for the first time, a classical deposit long cited as evidence of Permian glaciation in America.' And yet, this very unit had been one of the reasons for the rejection of the entire notion of 'continental drift' by an earlier generation of geologists (see above).

There were more surprises in store as new sedimentological approaches forced a reassessment of the practice of simply lumping together any poorly sorted or 'varved' rocks as 'glacial'. The seminal work of Crowell (1957), Dott (1961) and Winterer (1963) had led to the introduction of purely descriptive terms for poorly sorted and laminated facies that avoided any preconceived notion of a glacial origin (e.g, *diamict*, *mixtite*, *symmictite*, *rhythmite*; see Pettijohn, 1957; Flint et al., 1960; Harland et al., 1966; Schermerhorn, 1966). Nonetheless, important opposition remained to any reappraisal of Earth's glacial record, as evidenced by W.B Harland's bitter reference to 'this bleak period of disappointment' (Harland and Herod, 1975, p. 190).

3.1.4. The fourth snowball (1964): the 'infracambrian glaciation'

At the same time that sedimentology was shaking up the world of glacial geology and leading to a reassessment of the sedimentary record of ancient glaciations, the proponents of 'big glaciation' counter-attacked with intriguing geophysical evidence in support of low latitude glaciation. Harland and Bidgood (1959) reported magnetic data purporting to record equatorial paleolatitudes for Neoproterozoic glacials and invoked a huge 'infracambrian glaciation' of global extent involving 'near synchronous worldwide tillites' (Harland, 1964, Harland and Herod, 1975, p. 201). That tillites were found closely associated with carbonates was cited as additional evidence of huge fluctuations in global climates, recording 'one of the outstanding and exceptional physical events of Earth history' (Harland, 1964; p. 124). In the late 1950s, a handful of samples of Neoproterozoic rocks from northeast Greenland showed a remanent magnetism, indicating low paleolatitudes at the time of deposition and this spurred new thoughts on old glaciations (Bidgood and Harland, 1961b). This spawned a blizzard of debate and speculative geophysical models to explain glaciation from the poles to the equator (Crawford and Daily, 1971; Roberts, 1971, 1976; Sheldon, 1984; Malcuit and Winters, 1985; Fischer, 1986).

A consistent theme of this phase of study was to interpret ancient tillite successions and many Pleistocene deposits using a simple 'bed-for-bed', 'climatostratigraphic' approach. This is exemplified by most of the entries in Hambrey and Harland (1981) where poorly sorted deposits are commonly interpreted as the record of glaciations and interbedded facies as interglacials, thereby requiring extreme fluctuations of climate and sea level within a single stratigraphic succession. This approach is best illustrated by Spencer (1971) who set a new standard in the detailed lithostratigraphic description of Neoproterozoic sedimentary successions. As a consequence of detailed outcrop logging, he proposed that the Port Askaig Formation in Scotland recorded 17 different glaciations based on the presence of diamictite horizons (tillites) separated by other facies. Elsewhere, in keeping with simple climatostratigraphic extrapolation of climate from rock types, fine-grained laminated deposits were interpreted as glaciolacustrine 'varvites' (e.g., Sayles, 1919) and cited as evidence of markedly seasonal Neoproterozoic climates. Sedimentary dykes and wedges and other deformation structures were interpreted as the subaerial product of severely cold permafrost climates (Spencer, 1971).

3.1.4.1. Global glaciation refuted: 'a myth'. In the early years after 'continental drift' was replaced by 'plate tectonics' (McKenzie and Parker, 1967), geologists began to systematically apply the theory to hindcast ancient paleogeographies. Schermerhorn (1974a) led the charge in reexamining ancient glacial deposits in the light of their tectonic and basinal setting. Building on the work of Crowell (1957) and others, he argued that many supposed Neoproterozoic 'tillites' are nonglacial debris flows of unknown climatic significance, deposited in tectonically active marine basins marginal to uplifted source areas. He demonstrated that the common association of 'tillites' and carbonates was simply the product of active tectonic settings in which nonglacial marine mass flows were interbedded with olistostromes, debris flows and turbidites composed of detrital carbonate (Schermerhorn, 1974a). The worldwide distribution of diamictites that had impressed so many earlier geologists reflected the former close proximity of such strata within an earlier supercontinent followed by a long history of subsequent plate movements. He identified the importance of tectonic uplift in generating regional ice covers and also stressed the poor dating control on most deposits. Other confirmatory work followed such as Martin et al.'s (1985) detailed and lengthy refutation of the glacial origin of Namibian Neoproterozoic diamictites.

Schermerhorn argued that the occurrence of dropstones, striated clasts and pavements points to a glaciclastic source for *some* deposits, but, if present, glaciers were located on uplifted hinterlands and played no direct depositional role other than to supply sediment to the marine environment (Schermerhorn, 1974a,b; 1975; 1983). He also drew attention to the production of striated clasts by tectonic processes and the misinterpretation of coarse-grained debris flows as 'dropstone' horizons (see below). These findings were not well received by proponents of 'big glaciation' in the Neoproterozoic and, much debate, some of it, fairly acrimonious, ensued (e.g., Roberts, 1977; Schermerhorn, 1977).

With the benefit of hindsight, Schermerhorn's arguments were overstated because he viewed *all* Neoproterozoic diamictite deposits previously labelled as glacial, as tectonically induced mass flows despite convincing evidence for glacial conditions in many areas (such as in West Africa; e.g., Deynoux et al., 1976). Schermerhorn's (1974a, p. 813) statement that 'no Late Precambrian ice age or ice ages existed' is not only incorrect, but contradicts earlier statements made in the same paper such as where he writes 'if, then, truly glacial clasts or ice-dropped erratics occur to some extent in a number of these formations, it appears more plausible that they represent a minor glacial contribution, perhaps derived from local mountain glaciers. . .than they are indicators of an extensive ice age which failed to express itself in other ways'. He also stated, 'the subject of interaction of glacial and nonglacial factors and how to discern their proportions in the products. . .will require much more study' (Schermerhorn, 1974a, p. 811). The key point greatly relevant to modern studies is that Schermerhorn recognised that most ancient diamictites were not deposited by glacial processes sensu stricto and that many are, in fact, nonglacial and carry no paleoclimatic significance. Establishing criteria for recognition of glacial deposits and their differentiation from other poorly sorted and nonglacial rocks was to be the challenge for the next generation of investigators using new methods of looking at sedimentary rocks.

3.1.5. Facies and basin analysis methods applied to glacial deposits

Schermerhorn's work occurred against a backdrop of increasingly sophisticated studies of modern and Pleistocene glacial deposits prompted by new facies analysis methods. By the 1970s, modern glaciers were increasingly being used as depositional analogs for Pleistocene deposits. One of the first findings to emerge was that complex stratigraphic successions, containing multiple beds of diamict, could originate within a single episode of glaciation (e.g., Boulton, 1972; Boulton and Eyles, 1979; Lawson, 1979; Powell, 1981). At a stroke, this rendered invalid the simple 'bed-for-bed' interpretations of paleoclimate that had dominated previous climatostratigraphic work. Unfortunately, this lesson was not widely appreciated by those working on pre-Pleistocene deposits largely because of a lack of communication. Modern and Pleistocene deposits were principally studied by physical geographers interested in depositional processes, whereas lithified deposits of the pre-Pleistocene were studied by geologists primarily interested in stratigraphy. Additional complications were created because very few workers in either camp had any direct experience of modern glaciers. Many simply assumed that Neoproterozoic environments had essentially been replicas of Pleistocene conditions thereby ignoring the central role of tectonics in dictating depositional facies and preservation potential resulting in a stratigraphic record biased toward marine not terrestrial deposits. Dreimanis (1983) usefully reviewed what was then known of till forming processes and cautioned against using a simple uniformitarian approach to the pre-Pleistocene. A growing body of information was by then already indicating that such deposits are rare in the ancient record as a result of selective destruction of subaerial deposits and selective preservation of the marine record (Nystuen, 1985).

The emergence of detailed facies descriptions of glacial sediments emphasising paleoenvironmental reconstruction (Eyles et al., 1983) reflected the maturing of the discipline of sedimentology and its growing separation from stratigraphy per se (see Miall, 1995). The facies approach unified the hitherto separate work of geologists and physical geographers and resulted in a much improved understanding of terrestrial and marine glacial processes, sedimentary products and depositional systems (e.g., Benn and Evans, 1998; Anderson, 1999). Similarly, sedimentologists now recognise that a wide range of depositional processes, ranging from glacial to glacially influenced to nonglacial, are all capable of producing poorly sorted diamicts, laminated sediments and clastic wedges rendering direct climatic extrapolation from these rock types invalid. The terms till and tillite are now vested with specific genetic meaning; 'diamict(ite)s deposited directly from (usually below) glacier ice'; in practice, defining what sedimentologists call a *basal till* (see below).

An important development has been the application of 'basin analysis techniques' (Miall, 1991) to Pleistocene and pre-Pleistocene glacial deposits (e.g., Nystuen, 1985; Miall, 1985; Visser, 1991; Young and Gostin, 1991; Eyles, 1993; Eyles et al., 1983; Brookfield, 1994; Proust and Deynoux, 1994; Crowell, 1999; Bennett et al., 2002). Much new data regarding Earth's ancient glacial record has come from access to subsurface data such as core and geophysical data often on a basin scale. Such work has constrained the overall setting of glaciation in Earth history such that ancient glacial sediments can no longer be studied in isolation from their overall plate tectonic and basinal context. Renewed appreciation of the role of tectonics in promoting glaciation and allowing the preservation of a glacially influenced sedimentary record has given rise to a somewhat paradoxical conclusion that most so-called ancient glacial deposits are not terrestrial in origin but were preserved in marine basins. This work proved the essential correctness of Wegener's and Schermerhorn's views that most of Earth's 'glacial' record is selectively preserved in marine basins that lay marginal to centres of glaciation and were sites of active tectonism. With the exception of the extensive Neoproterozoic glacial deposits preserved across Northwest Africa (Deynoux et al., 1976; Section 4.1.3), Schermerhorn's central conclusion that 'no extensive continental tillites of Late PreCambrian age, resting on emerged land areas, are known' has been confirmed. The role of glaciers has been to act as large dump trucks, bringing in large volumes of clastic sediment to a basin margin where it was then redistributed by 'normal' sedimentary processes. Little of the landward record of ice covers has survived.

An additional challenge revealed by recent work is that long-term accumulation of glacially influenced marine stratigraphic successions is not simply controlled by climate and glacially driven changes in sea level, but by changes in relative sea level conditioned by tectonics. As a result, the record of glacio-eustatic sea-level variation is masked by long-term relative sea level changes conditioned by basin tectonics. This creates a major problem for paleoclimatologists attempting to resolve the geographic location of the principal terrestrial ice centres and their volume. As we shall demonstrate, these and other problems have not been recognised by proponents of a 'Snowball Earth'.

3.1.6. *The fifth snowball (ca. 1998): 'Snowball Earth'*

The Snowball Earth of Hoffman et al. (1998b) is a bold reworking of the global glaciation models of earlier workers and incorporates much new geochemical and paleomagnetic data. The model owes much to Cold War concepts of a 'nuclear winter' where dust veils thrown up by nuclear explosions lower global albedo resulting in 'complete glaciation of the world' (Budyko, 1969, 1999, 1982, p. 269; Sellers, 1969, 1990). Hoffman et al. (1998b) proposed a runaway albedo mechanism for initiating Snowball glaciation, where extreme cold and sea ice many kilometres thick shut down all hydrologic activity and chemical weathering such that marine autotrophic activity and organic carbon burial would cease. After some 5–10 million years, sufficient volcanically emitted CO_2 would accumulate to produce global temperatures of + 50 °C starting the catastrophic meltdown of ice. The principal stratigraphic and sedimentological assumptions underlying the Snowball Earth will be reviewed systematically below.

3.2. Stratigraphic and sedimentological assumptions behind the snowball model

The Snowball Earth model has been called a ‘script for global catastrophe’ (Runnegar, 2000). In response to very low concentrations of atmospheric carbon dioxide (around 150 ubar) and fainter sunlight (by some 6%), arctic glaciers invaded the equator, the oceans froze to depths of 1 km and biological activity was essentially put on life support in the face of extreme global temperatures. A mechanism for plunging the Earth into a permafrozen state ‘without parallel in the Phanerozoic’ (Hoffman and Schrag, 2002, p. 129) is proposed by these workers. Using a simple two-dimensional energy-balance climate model, he argued that if the Earth’s climate were to cool to the point where ice was to form at latitudes lower than 30°, a runaway albedo feedback effect would be created. This would cause global temperatures to plummet resulting in a completely frozen planet recorded by synchronous deposition of tillites below enormous ice sheets. Heat from the Earth’s molten interior would prevent the oceans from freezing solid, but would still allow a kilometre thick cap of sea ice to form. Kirschvink (1992), and later (Hoffman et al., 1998b; Hoffman and Schrag, 2000), proposed that volcanic activity and the build up of CO_2 would save the planet from perpetual refrigeration. During global refrigeration, all CO_2 sinks would be malfunctioning or nonexistent in the absence of any hydrologic cycle. Models suggest that once CO_2 reached 350 times the present day value, greenhouse warming would initiate rapid melting of the global ice sheets (Caldeira and Kasting, 1992). Based on current values of volcanic outgassing, it was estimated that individual global snowball conditions could have persisted for approximately 5–10 million years.

Ultimately, evaporation associated with melting of a global ice sheet would add water vapour into the atmosphere, enhancing the CO_2-induced greenhouse effect. As a consequence, sea ice hundreds of metres thick would disappear within a few hundred years. A vigorous hydrologic cycle and carbonic acid precipitation would rapidly weather frost-shattered and glacially abraded rock. Cations and bicarbonate would flood back to the oceans where they would neutralize surface water acidity and cause massive and rapid precipitation of inorganic carbonate sediment as stratigraphic ‘caps’ above glacial rocks. In turn, so the theory goes, brutal environmental changes may have stimulated the Cambrian ‘explosion’ some 535 million years ago.

It has to be said that a difficulty in assessing the model arises because much basic data has been presented as abstracts (Prave and Hoffmann, 1995; Hoffman et al., 1999; Halverson et al., 1999; Corsetti and Kaufman, 1999), *GSA Today* (Hoffman et al., 1998a), short papers in *Science* (Hoffman et al., 1998b) and *Scientific American* (Hoffman and Schrag, 2000), a recent brief discussion for *The Australian Geologist* (Hoffman and Maloof, 2001), and a review article (Hoffman and Schrag, 2002). This approach has prevented presentation of a sufficiently thorough sedimentological database and adequate review and discussion of previous stratigraphic and tectonic work. The following sections critically examine 10 principal assumptions underpinning the snowball model.

3.3. Diamictites are glacial

It is still a commonly held belief among many geologists that massive Neoproterozoic diamictites are necessarily glacial in origin (i.e., were deposited as tillites or ice-contact glaciomarine and glaciolacustrine deposits) and thus record the existence of glaciers in any one sedimentary basin. Large rafts of older underlying strata, typically blocks of carbonate, are commonly present within diamictites and are thought to record subglacial erosion and glaciotectonism in ice-contact environments (e.g., Hoffman et al., 1998b). The interbedding of diamictites (interpreted as tillites) within thick successions of deep marine facies, typically turbidites, is cited as evidence that glaciers reached sea level. Furthermore, paleomagnetic data suggest deposition near the equator. This, it is argued, rules out ‘normal’ glaciation on uplifted rift flanks because tropical glaciers must have been of large enough volume for ice margins to reach sea level. To explain this phenomenon, an extraordinary global climate event is invoked. The entire argument is based on misunderstanding of the origin of sedimentary successions because diamictites are not necessarily *directly glacial* in origin most commonly comprising part of thick, deep marine fan/slope successions. In the absence of independent evidence for glaciation, such facies have no unique climatic interpretation as they are deposited in marine basins regardless of latitude.

3.3.1. Common vs. universal facies types and the importance of 'context' in the interpretation of diamictite facies

Diamicts (sediment) and *diamictites* (rocks) are 'problematic' facies types to interpret simply because they are *common*. This is to say that exactly the same facies type (e.g., massive diamictite) can be produced in a very broad range of sedimentary environments. Ripple cross-laminated sandstone is another common facies type because ripples can form in a wide range of environments both marine and nonmarine by wind-driven currents, by rivers or gravity-driven currents. Diamictites (or rippled sandstone) are not *universal* facies that are produced under very specific depositional conditions. A good example of a universal facies type, providing an unambiguous paleoenvironmental solution, is hummocky or swaley cross-stratification in sandstones deposited by storm waves in relatively shallow, agitated waters.

Sedimentologists recognise that the correct interpretation of the paleoenvironmental setting of common facies types ultimately rests with analysis of the *context of deposition* provided by facies lying conformably above or below. This approach depends on there being a conformable depositional succession with no disconformities. This is the basis for Walther's Law which states that facies found conformably in a vertical succession, and which are thus temporally related, were once *spatially* contiguous within the overall depositional setting. Those facies are thus genetically related within what is now termed a depositional system. Other clues clearly come from any fossil material, but this is a luxury unavailable to the student of Neoproterozoic diamictites (with some significant exceptions as we note below).

The following section provides a brief review of genetic varieties of diamictites and identifies those types that are most commonly encountered in the Neoproterozoic.

3.3.2. Genetic varieties of diamictites

Observation of diamict-forming processes in modern environments indicates that such facies accumulate in many geological settings (Fig. 1). They can be grouped genetically as follows:

1. *Glacial*:

   Diamicts are created and deposited under ice sheets as a consequence of intense subglacial deformation and mechanical mixing of substrate sediments (*deformation till*: B; Fig. 1) (Boulton, 1996; Boulton and Dobbie, 1998; Boulton et al., 2001; Boyce and Eyles, 2000), by subglacial lodgement of englacial debris held within the ice base (*lodgement till*: C; Fig. 1), or, more rarely, by passive melt-out of englacial debris (*melt-out till*: D; Fig. 1) (Paul and Eyles, 1990; Benn and Evans, 1998). Such facies are normally thin (< 50 m) and rest on major unconformity surfaces.

   Glacial diamicts may also be deposited as subaqueous or terrestrial debris flows where sourced *directly* from ice (e.g., the subaerial and subaquatic *flow tills* of the older literature: A; Fig. 1).
2. *Glacially influenced*:

   Diamict facies are formed subaqueously on basin floors through the combined action of iceberg rafting of debris, ice keel 'ploughing' (turbation) by grounding ice masses, and deposition of mud from suspension ('rainout' diamicts: E; Fig. 1) (Eyles and Eyles, 1983; Dowdeswell et al., 1994). Similar facies can occur in cold but nonglacial settings where debris is rafted by seasonal ice (Dionne, 1993). Poorly sorted sediment gravity flows and debris flows (*debrites*), containing reworked glaciclastic sediment, occur on continental slopes surrounding glaciated margins. They also form in land areas of steep topography (e.g., so-called *para*-glacial deposits). Here, the term 'glacially influenced' is in recognition that sediment was supplied by glaciers (glaciclastic or glacigenic sediment), but was reworked and finally deposited by nonglacial processes.
3. *Nonglacial*:

   Diamict facies can form in cold, nonglacial environments (so-called *periglacial* settings) by mechanical weathering of bedrock or sediment, and downslope flow. Elsewhere, poorly sorted sediment gravity flows and debris flows occur widely in subaqueous or terrestrial nonglacial settings as a result of downslope slumping and mass flow such as in volcanically influenced settings (e.g., *lahars*: F; Fig. 1) (Waythomas and Wallace, 2002), on the steep unstable flanks of carbonate reefs (calcareous debris flows, *megabreccias, olistostromes*: G; Fig. 1) (James and Kendall, 1992) or continental slopes and fan deltas by the mixing of coarse and fine sediments (*mixtites*: H; Fig. 1) (Nemec and Steel, 1984; Einsele, 2000).

Diamictite facies can be formed by abrasive movement along faults (*fault gouge*; I; Fig. 1).

Diamicts frequently form as lag deposits or by *in situ* weathering of substrates (e.g., *boulder clay regoliths* with corestones: J; Fig. 1).

Diamicts can form subaerially, subaqueously or intraformationally (as intrusive bodies) as a consequence of meteorite or asteroid impact (*impact breccias*, *injection breccias*, *suevites*, *pseudotachylites*, etc.; K; Fig. 1) (Parmenter et al., 2002). Past attempts to argue that many tillites are ejecta (Oberbeck et al., 1993; Rampino, 1994) were unconvincing (Young, 1993).

3.3.2.1. Criteria for recognition of genetic types of diamict. The most useful criterion for identifying diamict(ite)s deposited in ice-contact glacial environments on exposed continental surfaces is rather simple; such deposits are characterised by stratigraphic complexity and restricted thickness (Eyles and Eyles, 1992; Benn and Evans, 1998; Plink-Bjorklund and Ronnert, 1999). They rest on marked regional unconformities, often striated and 'overdeepended', and show rapid lateral and vertical changes in facies types reflecting the highly dynamic nature of environments close to or under ice fronts. Far-travelled extrabasinal clasts are common; clasts are striated and 'glacially shaped' akin to bullets (Boulton, 1978; Benn and Evans, 1998). Strata deposited within any one glacial cycle are usually less than 100 m in thickness reflecting rapid rates of sediment dumping and the lack of accommodation space under or immediately in front of glaciers. Ice-contact strata experience repeated reworking and resedimentation especially during deglaciation when large volumes of meltwater are released and isostatic uplift promotes erosion. As a result, they have a reduced long-term preservation potential; in the long term, sediment will be dispersed and redeposited by normal nonglacial processes. The ultimate repository is the deep sea (Eyles, 1993).

Few Neoproterozoic diamictite successions show characteristics typical of glacial deposits that have accumulated below or at the margins of terrestrial glaciers or ice sheets, with notable exceptions (Deynoux, 1985). Debate continues even in the case of well-studied examples of ancient tillites (Reusch, 1891; Jensen and Wolff-Pedersen, 1996; Laajoki, 2002). The typical Neoproterozoic diamictite deposit is *stratigraphically simple* consisting of thick diamictite units (e.g., 800 m for those of the Chuos Formation of Namibia; Section 4.1.4.1; 3300 m for the Pualco 'Tillite' of South Australia; Section 4.1.7.1) that are conformably interbedded with slope and basin plain turbidites forming successions that are *extremely thick* (e.g., 8 km for the Macaubas–Salinas Group of Brazil; Section 4.1.5). The overall architecture of such deposits is sometimes remarkably simple (e.g., Fig. 2H). Diamictites are commonly associated with large olistostromes, slumps and megabreccias dominated by local debris recording massive submarine landsliding from earthquake-prone, basin-bounding faults.

Most Neoproterozoic diamictites are submarine debrites recording the storage of large volumes of coarse and fine sediment in shallow water and the subsequent reworking downslope in rift basins. *Regardless of latitude or climate*, enormous volumes of massive, stratified and poorly graded diamictite facies can be generated and deposited offshore by subaqueous mass flow as a result of faulting, depositional oversteepening, erosion of shelf edges, volcanic and earthquake activity as a result of rifting. The reader is referred to Koster and Steel (1984), Einsele (2000, pp. 210–234) and Mulder and Alexander (2001) for comprehensive reviews of submarine mass movements and gravity flows leading to the deposition of thick and areally extensive diamicts in a wide range of depositional and tectonic settings. Individual debris flows can travel large distances and form diamict sheets hundreds of metres thick; the largest are so-called 'compound mass movements' involving the mass movement of muddy slope sediments in response to sudden loading by slumps or slides originating upslope (e.g., Moore et al., 1982; Masson et al., 1998) much in the manner proposed by Crowell (1957), Schermerhorn (1974a), Nemec et al. (1984), Eyles (1990) and Eyles and Eyles (2000). Collapse of the shelf break results in the incorporation of olistostromes and breccias within debris flow deposits (Einsele, 2000). For this reason, Schermerhorn's term 'mixtite', although fallen from recent usage, is an entirely appropriate genetic term for most Neoproterozoic diamictites and its further usage is warranted. The central challenge in the interpretation of such facies is to identify where there was a glacial influence and if any glaciclastic sediment was incorporated into the debris flows.

All these points have been made at length in the past (Crowell, 1957; Schermerhorn, 1974a; Martin et al., 1985; Eyles, 1993), but the misconception that massive diamictites are necessarily glacial in origin still continues. Nowhere do the proponents of the snowball model or its later disciples (e.g., Sohl et al., 1999; Kennedy et al., 2001a) adequately acknowledge the earlier investigations and cautionary conclusions of Schermerhorn (1974a) and Martin (1965). A major limitation of much recent 'Snowball' work is that deposits are not described and presented using modern facies and basin analysis approaches. As evidence we offer the following statements made with regard to Neoproterozoic diamictites: 'objections to the hypothesis on sedimentological grounds...that widespread diamictites are nonglacial, possibly related to debris flow in tectonically active basins...are easily addressed because there is ample evidence of glaciation' (Sohl et al., 1999; p. 1121); and that of Prave (1999) that thick mass flow diamictite deposits in the Neoproterozoic 'are relatively minor features'. Neither statement is supported by the global stratigraphic record and contradicts earlier conclusions of Schermerhorn (1974a) and many subsequent authors. The very great thickness of debris flow and turbidite facies in the Neoproterozoic record points to enhanced delivery of very substantial volumes of sediment to basin margins. This is also completely at odds with the notion of global refrigeration and the assumed cessation of all hydrologic activity and sedimentary processes by the Snowball model (see McMechan, 2000 for discussion).

Conclusion. The assumption that Neoproterozoic diamictites are axiomatically glacial deposits is widely rooted in the literature. However, it cannot be sustained in the light of increased knowledge of the wide range of sedimentary and tectonic environments in which poorly sorted diamictite facies are produced. Interpretation of depositional and tectonic context indicates that *most* Neoproterozoic diamictites are deepwater debris flows indicative of tectonically active basins and carry no unique paleoclimatic interpretation.

3.4. Worldwide distribution of glacials requires global ice cover

Adherents of the Snowball model commonly assume that because diamictite deposits (which they uncritically accept as glacial; Section 3.3) are present on virtually every continent (including Antarctica, Stump et al., 1988) they must record a global glaciation (Lindsay, 1989, p. 206). Thus, 'the global distribution of glacial deposits of Neoproterozoic age suggests that the ice sheet of the time developed even to the equatorial area' (Tojo et al., 1999). The global extent of supposed Neoproterozoic glacial strata according to Hoffman and Schrag (2002, p. 130) has 'never fitted comfortably with Phanerozoic stereotypes', implying the need for a nonuniformitarian global snowball model. This logic has been exported back in time to the Paleoproterozoic where according to Bekker et al. (1999) 'evidence of three glaciations in the early Paleoproterozoic...of North America...and at least one on three other continents suggests that these ice ages were of global extent'. Therefore, the reasoning goes, Proterozoic glaciations were unlike any subsequent glaciations of the Phanerozoic 'because they can be found on every continent...unlike the more areally limited distribution of Pleistocene glacial deposits' (Sohl et al., 1999, p. 1121). To some, the Neoproterozoic deposits 'suggest climatic extremes unrivalled in Earth history' (Kennedy et al., 2001a, p. 1135) and ice ages 'unlike any in Phanerozoic Earth history because of their great severity' (Sohl et al., 1999, p. 1120). We believe these conclusions to be fundamentally incorrect as they are based on misinterpretation of the origin of diamictites.

3.4.1. Conclusion

The argument that pole-to-pole glaciation is required to explain a global distribution of diamictite deposits rests on the invalid assumption that all such deposits are glacial and chronostratigraphically equivalent (see below).

3.5. Glacial strata are chronostratigraphic marker horizons

Because glaciation is regarded by some as an unusual event in Earth history, diamictites are seen as *precise* chronostratigraphic markers (event horizons) co-eval with similar strata elsewhere around the world (Ojakangas, 1988; Chumakov, 1981, 1985; Kennedy et al., 1998; Abolins et al., 1999). Neoproterozoic 'tillites' are still used as a datum for interregional and global correlations (e.g., Knoll, 2000; Narbonne and Gehling, 2003). Consider the following statement from Lindsay et al. (1996; p. 391): 'Neoproterozoic diamictites of glacial origin have been recognised on all continents...Their widespread distribution suggests the development of ice sheets over large areas of the planet during Neoproterozoic time. The recognition of such major climatic events is in itself significant. Perhaps of greater importance, however, is the fact that these events appear to be synchronous and may thus be of considerable value in correlation.' This completely ignores their depositional origins and strong intrabasinal tectonic controls on deposition and age. The association of diamictites with banded iron formations (BIFs) has also been cited as a lithostratigraphic 'motif' of discrete worldwide Sturtian glaciation events (Kennedy et al., 1998).

The presently available geochronometric database is slim but suggests a wide variation in age of deposits between 750 and 610 Ma (Evans, 2000; Table 1). Thus, it cannot be rigorously demonstrated *as yet* whether (a) there are two separate (but broadly defined) intervals of Neoproterozic glaciation such as Surtian and Marinoan, (b) whether there was diachronous glaciation during the entire Neoproterozoic, or (c) a combination of (a) and (b). What is clear however, is that despite the assumption of synchroneity of glacial events made by proponents of a Snowball Earth it cannot be proved (or disproved) by the available radiometric age database.

3.5.1. Conclusion

The assumption that Neoproterozoic glacial strata were deposited synchronously rests, in turn, on another assumption that diamictites provide a unique record of one or more global glaciations.

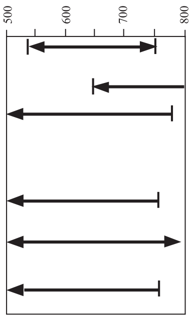
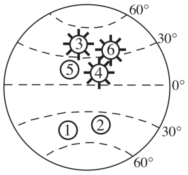
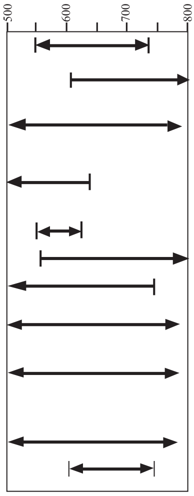
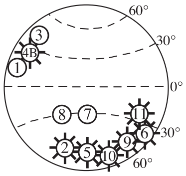
3.6. Banded iron formations require glaciation

Modern seawater contains less than one part per billion of iron because iron is relatively insoluble in its oxidized form (Fe^{3+}). Most banded iron formations (BIFs) are older than 1850 Ma and formed at a time when the atmosphere had little free oxygen and seawater in the deep ocean contained abundant iron. This iron was precipitated in upwelling zones where it encountered oxidizing surface waters (Simonson, 1985; Isley, 1995).

After a hiatus of over a billion years, the *limited* reappearance of BIFs in the Neoproterozoic sedimentary record suggest to some, globally significant environmental change. Hoffman and Schrag (2000, 2002) linked the formation of banded iron deposits with glaciation and suggested that the formation of anoxic seawater below a global cover of thick ice shelves maintained ferrous iron in solution. Kirschvink (1992) argued that during millions of years of ice-covered oceans, the deep ocean would become anoxic, allowing ferric iron (Fe2+) to build up to high concentrations. Once glaciation ended, the ocean would quickly become oxidized and the iron would precipitate out and would be deposited as a capping above glacial deposits.

Unfortunately, banded iron formations are not uniquely associated with Neoproterozoic diamictite deposits. They are absent from many, occurring either stratigraphically below such deposits or are demonstrably postdepositional (Williams and Schmidt, 2000; Young, 1988, 1995; Fig. 3). The link with diamictite deposits is simple; both were deposited in extensional tectonic regimes. Neoproterozoic banded iron formations formed in enclosed or partially restricted rift basins from metal-rich brines, often invading laminated turbidite facies deposited in deep water (see Young, 1995; Eisbacher, 1985). In most cases, 'glacial' deposits are predominantly coarser-grained sediment gravity flows (diamictites, conglomerates) deposited within the same rift basin. Neoproterozoic banded iron formations and 'glacials' are the different stratigraphic

Table 1
Summary table of principal Neoproterozoic diamictite deposits, origin, age and inferred tectonic setting

Continent/ Block	Geographic Location	Basin/ Formation	Tectonic Setting	Dep. Env't	Glacial Influence	Age Constraint (Ma)	Paleolatitude Estimate
Sturtian/Raptian after 750 Ma							
1. S.Africa	Naniba	Chuos Fm	RIFT	slope?	ND		
NE. Africa	Oman	Fiq Fm	RIFT	slope?	DEM		
2. Amazona	Brazil	San Francisco	RIFT	slope/base	ND		
3. Australia	central Australia	Yadnamutana Subgroup	RIFT RIFT	of slope slope/base of slope	DEM ?		
Asia	Mongolia/Siberia	Tsagaan Oloom Fm	RIFT	?			
4. Laurentia	western North America	Windermere Sg/ Shezal Fm/Vreeland	RIFT	slope	DEM		
5. Laurentia	southwestern United States	Kingston Peak Fm/ Surprise diamictite	RIFT	slope?	ND		
6. South China Block	Yangtze Platform	Changan/ Nantuo Fm	RIFT	marine	DEM		
MARVE Marinoan/Vendian/Ice Brook/Sinian after 610 Ma							
1. Africa	Namibia	Ghaub Fm	RIFT	slope	ND		
2. Africa	northwest Africa	Taoudeni Basin	CONV	foreland basin	DEM		
3. Amorica/ Cadomian	France	Granville Fm	RIFT	slope/deep mar.	ND		
	New England	Boston Bay Gr./Squantum	ARC	slope	ND		
	Virginia	Konnarock Fm	RIFT	slope?	ND		
4A. Australia	southern Australia	Elatina Fm	RIFT				
4B. Australia	northern Australia	Moonlight Valley Tillite*			DEM		
5. Avalonia	Newfoundland	Gaskiers Fm	ARC	slope	DEM		
6. Baltica	southern Norway	Moelv Tillite	RIFT	marine	DEM		
7. Laurentia	western North America	Windermere Sg/ ice brook Fm	RIFT	slope	?		
8. Laurentia	southwestern United States	Kinston peak Fm/ Wildrose diamictite	RIFT	slope?	ND		
9. Laurentia/ Baltica/ Spitzbergen	Greenland/ northern Norway	Tillite Group/ Smalfjord Fm	RIFT	marine	DEM		
10. Laurentia?	Scotland	Port Askaig Fm	RIFT	shelf	DEM		
11. North China Block	Ningxia Province	Zhengmuguan Fm	RIFT	marine	DEM		

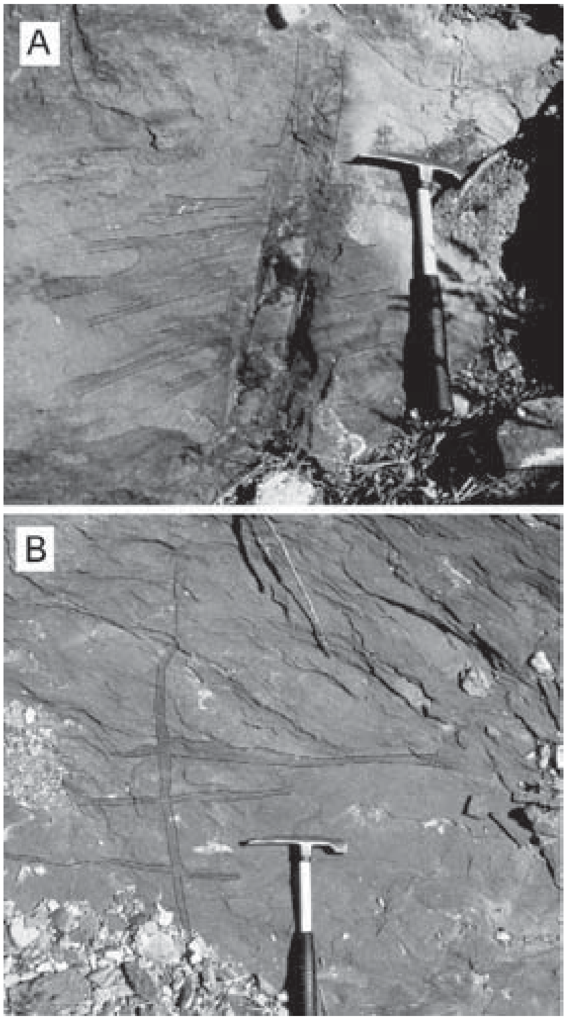


Fig. 3. A, B. Secondary iron formation. Hematite is emplaced vertically along postdepositional faults and joints and extends laterally as rootlike horizontal veins. Chuos Group, Namibia. Hammer (30 cm) for scale.

expression of the same tectonic setting, i.e., the rifting of continental crust during the breakup of Rodinia and associated hydrothermal activity from incipient mid-ocean ridges.

3.6.1. Conclusion

There is no genetic or temporal link between banded iron formations and Neoproterozoic glaciation sufficient to argue that deposition of banded iron is dependent on global ‘Snowball’ refrigeration. A more likely explanation of the reappearance of iron deposits is hydrothermal activity in embryonic rift basins accompanying the breakup of Rodinia after 750 Ma.

3.7. Paleomagnetic data provide ‘robust’ support for low-latitude glaciation

Phanerozoic continental ice sheets were controlled by latitude and altitude. For example, ice sheets of the Early and Late Paleozoic and Pleistocene, were restricted to intermediate to polar latitudes where snow lines intersected broad uplifted plateaux. Then, the equatorward growth of ice covers, other than on the tops of very high mountains, was prevented by rising snow line elevations. That the Neoproterozoic represented a radically different situation involving worldwide glaciations was suggested by Gevers (1931) and later Harland (1964). Harland and Bidgood (1959) and Bidgood and Harland (1961a,b) reported paleomagnetic data from Greenland implying Neoproterozoic glaciation at the tropics. These data were later shown to be unreliable, the result of postdepositional thermal overprinting during the Phanerozoic, but nonetheless the concept has survived on the basis of the ‘worldwide distribution of tillites’ (Kaufman, 1997; see Section 3.4). The thinking that underlies such a view not only assumes a direct glacial origin for deposits which cannot be demonstrated, but fundamentally ignores post-Neoproterozoic dispersion of once contiguous landmasses.

3.7.1. Sturtian database

The then available Neoproterozoic paleomagnetic database was reviewed by Meert and van der Voo (1994). They also presented additional new data for

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Note to Table 1:
Paleolatitude estimates and instances of demonstrated glacial influence are consistent with localized glaciation at latitudes near or greater than 30°. Age constraints are from absolute age dating techniques, not from comparison with supposedly time-correlative strata. Grey and Corkeron (1998) recognise a second, younger Marinoan glacial deposit in northern Australia, the Moonlight Valley Tillite. ND: glacial influence not demonstrated; ?: glacial influence questionable; DEM: glacial influence demonstrated. Age and magnetic data compiled from data in Meert and van der Voo (1994), Torsvik et al. (1996), Evans (2000) and Li and Powell (2001).

Laurentia, Baltica, China and parts of Gondwana such as Namibia. They concluded that Neoproterozoic glaciations 'may well all have occurred above 25° latitude' with the *single exception* of the South Australian record of Marinoan cold climates from the Adelaide Rift Complex (Table 1). Evans (1999) reviewed Neoproterozoic paleomagnetic data and classified them as either 'moderately reliable' or 'very reliable'. He concluded that 'very reliable data' demonstrating glacial deposition in low paleolatitudes, are limited to the Elatina Formation of South Australia and to the Rapitan Group of the Northwest Territories of Canada. This assertion is reviewed below.

3.7.1.1. Namibia (Chuos Group). Data from the Chuos Group of Namibia (one of the key outcrops for 'low latitude global glaciation') were categorized as 'moderately reliable' by Evans (1999). In fact, the available data indicate the presence of components of later remagnetization and thermal overprinting. Kröner et al. (1980) studied the remanent magnetization of Nama Group mixtites and identified a low paleolatitude. They concluded however, that magnetization was the result of thermal overprinting acquired as a result of metamorphism during the Damara Orogeny and was thus an unreliable record of original paleolatitude. Despite this finding, Kröner (1981, p. 176) later wrote that the data 'suggests deposition near equatorial latitudes'. Meert and van der Voo (1994) concluded that 'a clear resolution of the paleolatitudes of the southern African–Namibia glaciations requires better dated paleomagnetic poles'. The lack of reliable Neoproterozoic paleomagnetic data from the Congo craton was stressed by Dalziel et al. (2000) and Powell and Pisarevsky (2002). The position of the Congo craton within Rodinia at about 1 Ga can be broadly constrained by similarities with the geology of the Kalahari craton and the known position of the latter relative to the Grenvillian-age Llano Orogenic Belt of eastern Laurentia (Unrug, 1997; Dalziel et al., 2000). Thus, it is assumed that the Congo craton lay outboard of the southeast margin of Laurentia just prior to Rodinian rifting at 750 Ma (Fig. 4A). Dalziel et al. (2000) stressed that the position of the Congo craton was not at all well known and its supposed equatorial position (Hoffman et al., 1998b) is entirely unconstrained by paleomagnetic data.

3.7.1.2. Canada (Rapitan Group). Morris (1977) showed the paleomagnetism of the Rapitan Group to be complex consisting of at least three different components which he attributed to hydrothermal precipitation of diagenetic hematite. Park (1997) reexamined and resampled the Rapitan Group including the Mount Berg Formation that is interbedded with the 'glacigenic' Shezal Formation. No samples to date have been collected from the Ice Brook/Keele formations. Data from the Mount Berg Formation indicate a paleolatitude higher than 25°, while that collected elsewhere from the Rapitan only 'implies' (Park, 1997, p. 47) deposition at lower paleolatitudes. Given the obvious uncertainties in the analysis of Park (1997), we are unconvinced that such data are either 'very reliable' (Evans, 1999) or 'strongly suggest equatorial latitudes' during glaciation (Park, 1997, p. 47). In particular, we remain sceptical that knowledge of the acquisition and the interpretation of remanent magnetization in these hydrothermally affected and tectonically rotated strata has been fully resolved.

3.7.2. Marinoan

The work of Schmidt et al. (1993) and Williams (1993, 1998) on Marinoan 'glacials' of southern Australia is the paleomagnetic keystone of the 'equatorial glaciation' hypothesis and is regarded as 'robust' by several workers (Sohl et al., 1999; Evans, 2000).

3.7.2.1. Australia (Elatina Formation). Paleomagnetic investigations have focussed on the Elatina Formation which consists of very fine-grained laminated siltstones variously interpreted as glaciolacustrine varvites (Williams and Tonkin, 1985), nonglacial tidalites (Williams, 1989b), ice-contact glaciomarine tidalites (Sohl et al., 1999), or deepwater turbidites. Meert and van der Voo (1994) noted that Elatina strata were nonmetamorphosed, but nonetheless had been affected by the Delamerian Orogeny (mid-Cambrian to Ordovician) which elsewhere had produced tight folding and slaty cleavage, indicating the strong likelihood of postdepositional remagnetization (Schmidt and Williams, 1995, p. 111). Williams (1996) countered this claim by presenting results from a fold test on a single slab. They argued that results showed that detrital remnant magnetization was primary and had been subsequently affected by folds produced by earthquake-related slumping (later to be regarded as the

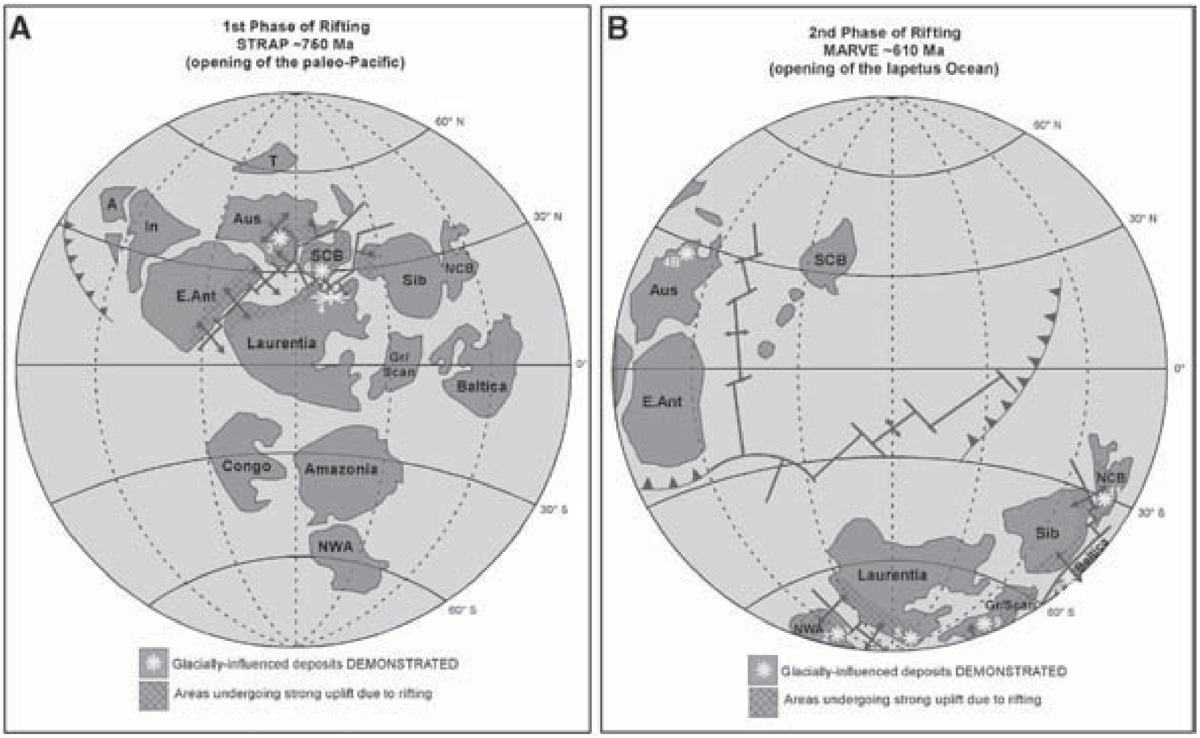


Fig. 4. (A) **STRAP**: First phase of Rodinian rifting after 750 Ma and the opening of the paleo-Pacific Ocean. (B) **MARVE**: Second phase of Rodinian rifting at about 610 Ma and the opening of the Iapetus Ocean. In both (A) and (B), rifting is depicted as a single synchronous event, but rifting of continental blocks would have been in the form of a 'zipper'. Diagonal striping indicates areas of strong uplift of rift flanks and passive margin plateau; asterisks indicate locations where a definite glacial influence on deposition has been demonstrated. Numbers are as in Table 1. A: Arabia; Aus: Australia; E. Ant: East Antarctica; Gr/Scan: Greenland/Scandanavia; Ind: Greater India; NCB: North China Block; SCB: South China Block; Sib: Siberia; T: Tarim; NWA: northwest Africa. (A) and (B) are compiled from data in Li and Powell (2001), Torsvik et al. (1996) and Meert and van der Voo (1994).

product of wave activity, Williams, 1996). They also recognised that the tidalites represented no more than 60–70 years of deposition and thus provided no constraints on secular variation. Schmidt and Williams (1995) rectified this deficiency and confirmed a palaeoequatorial setting.

Sohl et al. (1999) recognised that the harmonic 'soft-sediment folds' of Williams (1996) were very unlikely to be of a slump origin and thus did not provide an adequate test of when magnetization had occurred. They conducted further tests on the Yaltipena Formation immediately below the Elatina (called an 'unconformity test') and on clasts and matrix within diamictite (a 'clast test') at the base of the Elatina. Both tests yielded indeterminate results. Sohl et al. (1999) noted the presence of many 'uninterpretable data' (p. 1122) and 'unstable magnetizations' from 'crucial intervals of both formations' (p. 1125). They identified three components of magnetization (which they labelled A, B, C) only one of which (C) passed a fold test and was regarded as primary although they recognised the possibility of overprinting during burial and/or uplift and regional deformation associated with the Delamerian Orogeny (p. 1129–1130). They identified dual polarities from several sites and conducted a statistical evaluation that showed that such polarity changes were the product of different ages of magnetization. They defined distinct polarity 'magnetozones' present within widely separated outcrops of the Elatina, but found that 'an obvious feature of the polarity intervals...is the lack of consistency in the pattern of polarity changes from section to section' (p. 1131) and further, that the 'relatively small numbers of paleomagnetically reliable data points defining the polarity intervals...also cloud the issue'.

Uncertainties in paleomagnetic results were explained by Sohl et al. (1999) as being the result of a complex ice-contact depositional setting regarded as 'crossing from shallow-water to deeper-water environments'. This paleoenvironmental interpretation is very different from that made by Williams (1989a, p. 98; 1989b, p. 40; 1993), who identified a distal ebb-tidal deltaic setting on a deep (100 m) shelf; no mention was made of an ice-contact setting. In an entirely new interpretation, not supported by published or newly collected sedimentological data, Sohl et al. (1999) suggested that deposition took place close to a 'grounded ice margin' and associated 'subglacial tunnel mouths' (p. 1131). Evidence of an ice-contact glacial origin rests, apparently, on the presence of a 'pebble conglomerate' present on an 'unconformable surface' (*sic*) together with evidence of 'plastic deformation of the underlying, partially lithified sandstones of the Yaltipena Formation' (Sohl et al., 1999, p. 1122). An ice contact origin is difficult to reconcile with the widely accepted model where Marinoan ice covers are limited to *northern Australia* (W.V. Preiss, personal communication, 2000; Section 4.1.8.2). Powell et al. (1994, p. 121) stated that no Marinoan continental ice sheet was likely in southern Australia. Elatina stratigraphic logs presented by Sohl et al. (1999, their Fig. 10) provide no compelling sedimentological reasons to identify these strata as ice-contact glacial deposits; these strata could equally be non-glacial fluvial or shallow marine in origin. The reader is left with the question: *exactly what is being sampled and what was the paleoenvironment of deposition*? These are fundamental questions that need to be addressed before low latititude 'glaciation' can be fully accepted (see Section 4.1.7.2).

In consequence, we cannot agree with the conclusion of Sohl et al. (1999, p. 1133) that their work provides a 'very robust paleomagnetic survey of the Marinoan age glacial deposits'. There remain fundamental uncertainties regarding the origin and age of these strata and precisely when paleomagnetic characteristics were acquired. It can be noted, as a further example of uncertainty, that Williams (1989a) correlated the rhythmically laminated facies of the Elatina Formation with fine-grained turbidite facies interbedded with the 'Chambers Bluff Tillite' of the Officer Basin that is regarded by others as belonging to the much older *Sturtian* interval (Preiss, 1987). Sohl et al. (1999) stated with respect to the Elatina that 'the age is not surprisingly poorly constrained; the age limits of 610 and 575 Ma are based upon the presumed relationship of the Marinoan glaciation to Varanger glacial intervals elsewhere in the world' (see also Christie-Blick et al., 1995. p. 7). Thus, there are no real age constraints on the Marinoan and the question of precisely *when* a low latitude paleomagnetic signal was acquired becomes of great significance (e.g., Crowell, 1999; Fig. 4B; Table 1). In referring to the results of Sohl et al. (1999), Williams and Gostin (2001, p. 575) reemphasised that the timing of the magnetizations is poorly constrained.

3.7.3. Northwest Europe

3.7.3.1. Greenland. Early studies of the Tillite Group by Bidgood and Harland (1961a,b)_Hlt44229793] showed low paleolatitudes that are now agreed to be the result of early Paleozoic remagnetization (Abrahamsen, 1998; Evans, 2000).

3.7.3.2. Svalbard. No paleomagnetic data are available from the glaciogenic Petrovbreen Member and Wilsonbreen Formation within the Polarisbreen Group in northeast Spitsbergen. These strata are correlated with the Tillite Group in East Greenland (Harland, 1997).

3.7.3.3. Scandinavia. Paleomagnetic data from deep marine slope deposits that occur between the glacially influenced marine Smalfjord and Mortensnes formations are primary and indicate deposition in mid-latitudes between 30° and 40° (Torsvik et al., 1996). The Egersund dike swarm in southern Norway is thought to record the initiation of rifting and opening of the Iapetus Ocean when Baltica split from Laurentia after 620 Ma (Torsvik and Meert, 1995; Bingen et al., 1998; Evans, 2000).

3.7.3.4. Scotland. The paleomagnetic characteristics of the Port Askaig 'Tillite' has been studied for many years (e.g., Tarling, 1974) and the modern consensus is that the southerly low latitudes derived by early workers is the result of later remagnetiziation of Middle to Late Ordovician age and thus has no bearing on original paleolatitude (Glover et al., 1995; Soper and England, 1995).

Conclusion. Nicoaill et al. (2001) stated that ‘only one Neoproterozoic glacial deposit (the Elatina of South Australia) has yielded convincing evidence for low latitude deposition’ and that ‘one of the major limitations to a better understanding of Neoproterozoic paleogeography, and a possible Snowball Earth, is the scarcity of reliable paleomagnetic data from several of the major continental blocks’. We would stress however, that great caution is required because the age and origin of the Elatina has not been adequately demonstrated by detailed sedimentological study. The statement of Nicoaill et al. (2001, p. 557), that uncertainty in the paleomagnetic database affects the robustness of ‘the paleogeographic reconstructions. . .which bear on the claimed equatorial paleolatitudes of the glacial deposits’ is emphasised.

3.8. Intimate stratigraphic association of ‘glacials’ with carbonates requires extreme changes in climate

The presence of large amounts of clastic carbonate debris, composed of limestone and dolostone ranging in size from enormous olistoliths hundreds of metres in length to fine silt-sized matrix, is a very common feature of Neoproterozoic diamictite successions. In many cases, beds of reworked, clastic carbonate are present interbedded within or capping carbonate-rich diamictites. Past workers focussed on the mineralogy of the deposits and assumed them to be primary, thus requiring extreme climatic changes (e.g., Williams, 1993), giving rise to the notion that Neoproterozoic climates were ‘bizarre’ (Fairchild, 1993). Work has demonstrated that they record the shallow marine reworking of detrital carbonate (Fairchild, 1993; Fairchild et al., 1994) as a consequence of the cannibalisation of Mesoproterozoic shelf platforms during subsequent faulting and breakup of Rodinia. Other primary ‘postglacial’ carbonate deposits are separated from underlying ‘glacial’ strata by considerable thicknesses of marine rocks and/or unconformities (see below).

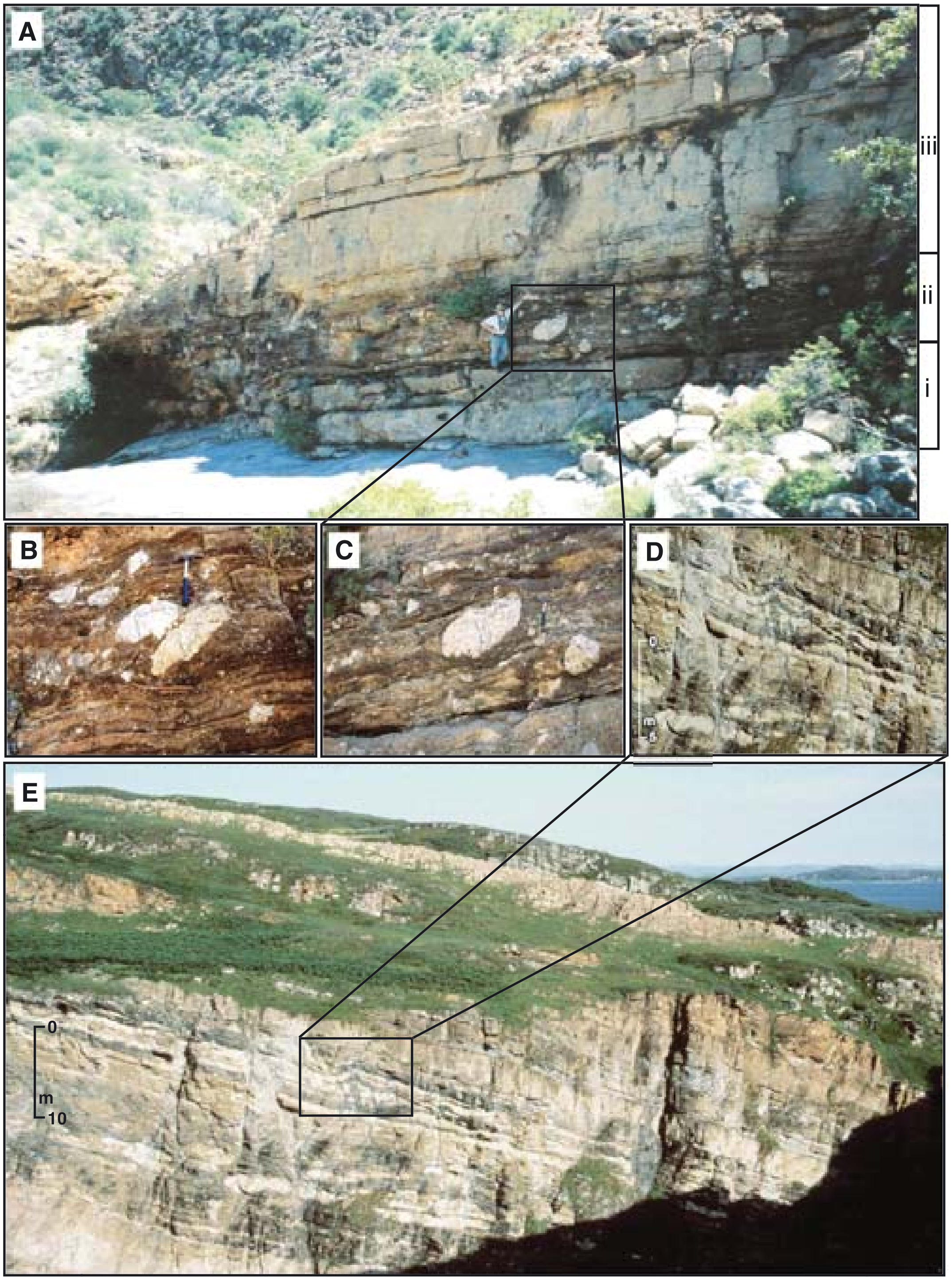
3.8.1. Olistostromes

A very common characteristic of Neoproterozoic rift successions is the presence of thick carbonate-dominated olistostromes interbedded with diamictites and turbidites. Large, often folded, olistolith blocks and thick beds of breccias record the downslope collapse of carbonate platforms broken apart by faulting (Kröner, 1981; McWilliams and Kröner, 1981; Spencer, 1971; Hambrey and Harland, 1981; Eisbacher, 1985; Martin et al., 1985; Aitken, 1991a; Eyles, 1993; Prave, 1996; Arnaud and Eyles, 2002). Strata, such as the ‘Great Breccia’ and ‘Disrupted beds’ of the Dalradian Port Askaig Formation in Scotland, have facies equivalents in many other Neoproterozoic successions (Fig. 5). Faulting triggers large landslides that are released from steep footwall slopes. ‘Megabreccias’ defined as ‘unsorted angular blocks and shattered masses of pervasively brecciated and transported rock’ are a common component of the stratigraphy of rift basins (Dickinson, 1991; Sengör, 1995). Olistostromes in Neoproterozoic deposits are therefore, an unambiguous indicator of tectonic setting. They provide prima facie evidence of faulting and the formation of unstable mass flow-dominated slopes generated as a result of continental breakup.

3.8.2. Interbedded and ‘cap’ carbonates

Much has been made of so-called ‘cap carbonates’ (designated here as ‘cc’) that overlie ‘glacial’ deposits and the occurrence of other carbonates interbedded with ‘glacials’ (‘ic’) implying very rapid changes in climate (Harland, 1964; Spencer, 1971). More recently, Fairchild (1993) highlighted the ‘sharp limits of glacial conditions’ (his Fig. 1.1) that he inferred from the occurrence of beds of clastic carbonates simply resting on beds of ‘glacial’ deposits. Hoffman et al. (1998b) similarly refers to ‘cc’ that ‘sharply’ overlie glacials; it is the obvious intent of both workers to imply that radical changes in paleoclimate are recorded (e.g., Fig. 11). In fact, as we show below, few detailed paleoenvironmental and petrographic studies have been published and fundamental questions, as yet unresolved, relate to their origin and depositional environment and their temporal relationship with underlying ‘glacials’.

3.8.2.1. ‘Cc’. Whereas the term ‘cap carbonate’ is in routine usage, and implies a relatively thin succession of carbonates conformably overlying glacials below, in practice the term is used for carbonates that are


A
iii
ii
i
B
C
D
E
0
m
10

thick (several hundred metres) and separated by hiatuses or major unconformities from glacials below. Thus, despite their designation as 'cap carbonate' deposits, any close temporal association with supposed glacial sediments is very tenuous (e.g., Saylor et al., 1998; Hoffman and Schrag, 2000, 2002). Kennedy (1996) reviewed the stratigraphic occurrence of Neoproterozoic postglacial carbonates in Australia and argued that 'cc' were deposited '*within the geologically brief period of postglacial transgression*' (p. 1050) which was also suggested by James et al. (2001) for the cap carbonate above the Marinoan Ice Brook Formation of Northwest Canada (see below). In the model of Hoffman and Schrag (2002) cap carbonates are ascribed to postglacial sea-level rise. In contrast, however, examination of Fig. 1 in Kennedy (1996) reveals very considerable thicknesses of strata (and thus potentially *millions of years*) between postulated 'glacials' and so-called 'postglacial cc' deposits. In most cases, Neoproterozoic 'cc' are separated from underlying glacials(?) by unconformities rendering invalid any assumption of an immediate 'postglacial' age. No 'cc' can unambiguously be demonstrated to be immediately *postglacial* in the climatic sense used by Pleistocene geologists when referring to the last 10,000 years since the disappearance of continental ice sheets. There is also similar uncertainty with respect to the notion that carbonates were deposited during postglacial transgression in view of the problem of identifying eustatic sea-level changes in the fills of tectonically active basins (see Section 3.11 below).

James et al. (2001) stated that "similarity in composition, vertical succession and lateral distribution of facies amongst Marinoan glacial cap carbonates worldwide supports a global precipitation 'event', coincident with extensive (?global) deglaciation". This conclusion needs to be tempered by recognition of the lack of detailed petrographic studies of 'cc' at other localities. Interestingly enough, James et al. (2001) are also circumspect about the role of global glaciation in creating cap carbonates. After completing one of the most detailed petrographic studies of a cap carbonate yet available, they concluded that 'a precise origin remains elusive'. Furthermore, the characteristics of the 'cc' are at odds with a Snowball Earth mechanism and fails to suppprt 'the required extreme postglacial changes in temperature and PCO_2' (James et al., 2001, p. 1258). We note that cap carbonates are *absent* above definitely glacially influenced deposits in Baltica (Kumpulainen and Nystuen, 1985). Available data shows a wide variation in stratigraphic position and characteristics of capping carbonates relative to marine strata below. As explained above, an immediate postglacial age (sensu stricto) cannot be demonstrated.

In view of some of the difficulties identified above, the term 'cap carbonate sequence' has been introduced by Hoffman and Schrag (2002). This recognises the considerable thickness of carbonate (and other) strata that rest on supposed glacial strata (e.g., 400 m in northern Namibia; see Fig. 9 in Hoffman and Schrag, 2002). Such thicknesses defy an origin related to abrupt, geologically instantaneous 'global deglaciation events'. Much has been made in the literature of the presence of primary 'crystal fan' carbonates in Namibia, but these unusual and intriguing deposits occur well above supposed glacials (e.g., Hoffman and Schrag, 2002). It is possible that such thick strata record the end of tectonic activity and the reestablishment of stable carbonate shelves and platforms (e.g., Fig. 6). A question arises as to whether the reworking of large volumes of clastic carbonate during rifting affected subsequent primary carbonate deposition. As with diamictite facies, more attention needs to be focussed on the tectonic significance of Neoproterozoic carbonate platforms within their broader basinal context. Hoffman and Schrag (2002, p. 142) contend

Fig. 5. (A, B, C) Crudely bedded diamictite facies (unit ii) with large freighted clasts; so-called 'Pip's Rock'; Ghaub Formation, Narachaamspos, Namibia. This facies has been described as a 'dropstone' unit recording meltdown of a Snowball Earth (Hoffman et al., 2000). The context of deposition is that of a deepwater slope at the base of a faulted carbonate platform (Fig. 6) receiving large volumes of poorly sorted sediment gravity flows. The unit rests on thick mass flow diamictites (unit i) dominated by clastic carbonate debris (Fig. 11). The 'dropstone unit' can be directly compared with other widely reported sediment gravity flow facies that transport outsized clasts (see Section 3.9). Debris flows are interbedded with and are overlain by thin-bedded turbidites (unit iii) composed of clastic carbonate ('cap carbonate' of Hoffman et al., 1998b; Fig. 11G,H). The same so-called 'cap carbonate facies' occur interbedded within diamictites (Fig. 11I,J,K). (D, E) Great Breccia, Port Askaig Formation of Scotland, showing rafts of carbonate within debris flows.

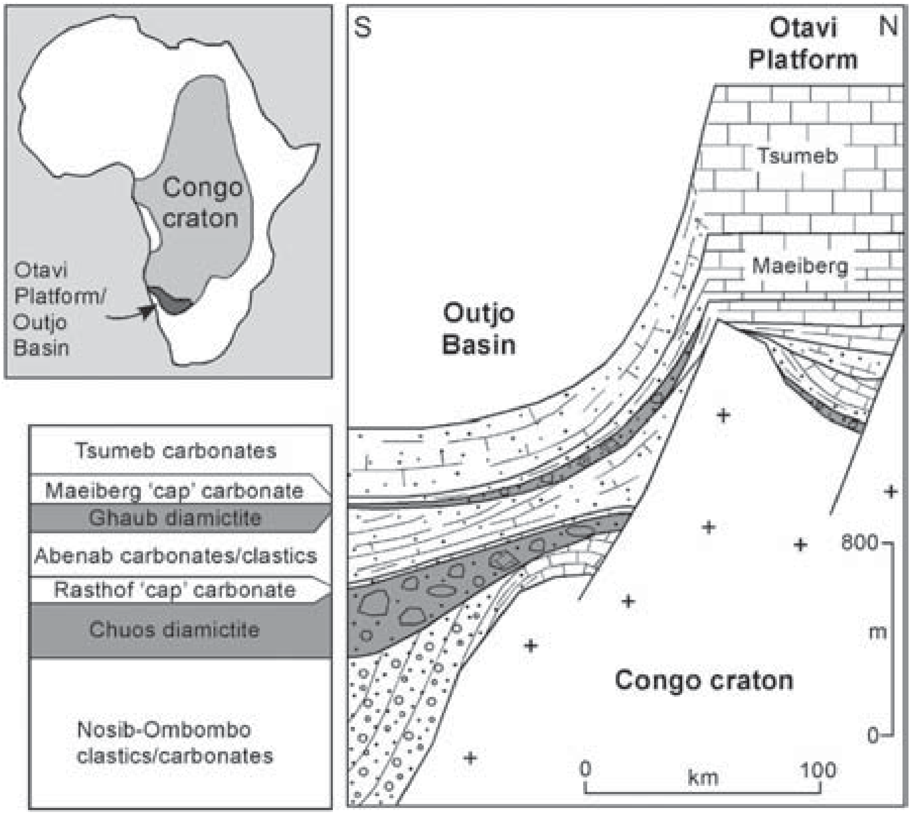


Fig. 6. Basinal setting of key 'Snowball Earth' successions in Namibia. Showing diamictites, associated turbidites and platform carbonates of the Otavi Platform and Outjo Basin (modified from Hoffman, 2002). A glacial influence on sedimentation cannot be recognised (Martin et al., 1985). As with many other Neoproterozoic successions, diamictites are deep marine mass flows recording rifting and collapse of carbonate platforms during multiple episodes of Rodinian rifting. Compare with Figs. 12B and 13. For sedimentary facies, see Fig. 11.

that 'in cap carbonates, we see the smoke, if not the gun, of the Snowball Earth'. Detailed sedimentological and petrographic studies, in the broader context of the tectonic setting of 'cap carbonate' deposits, are required to clear the smoke.

3.8.2.2. 'Ic'. Fairchild (1993) wrote of the 'paradox' of carbonates interbedded with Neoproterozoic glacial deposits, but solved the apparent riddle by clearly demonstrating that such an association is the result of a high content of *reworked* clastic carbonate. Previously reported dolostones (Spencer, 1971), for example, turn out to be clastic dolarenites. Crossing and Gostin (1994) also identified the importance of reworking of old carbonate in determining isotopic signatures in Sturtian glacials of South Australia. Primary 'precipitated' carbonates interbedded with Neoproterozoic glacials are distinctly different from true nonglacial warm climate carbonates of the Neoproterozoic. 'Glacial' precipitated carbonates are distinguished by their very fine-grained crystal size (less than 3 um) and lack of evidence of evaporative processes. They can be explained by syn-depositional dissolution and recrystallisation by Ostwald ripening of very fine-grained clastic carbonate particles (Fairchild, 1993). This is commonly seen in modern environments characterised by recycling of old carbonate (e.g., as occurs in the Canadian Rockies) where fine-grained, highly reactive carbonate readily dissolves and is reprecipitated as surface crusts (Fairchild, 1993; Fairchild et al., 1994 and refs therein).

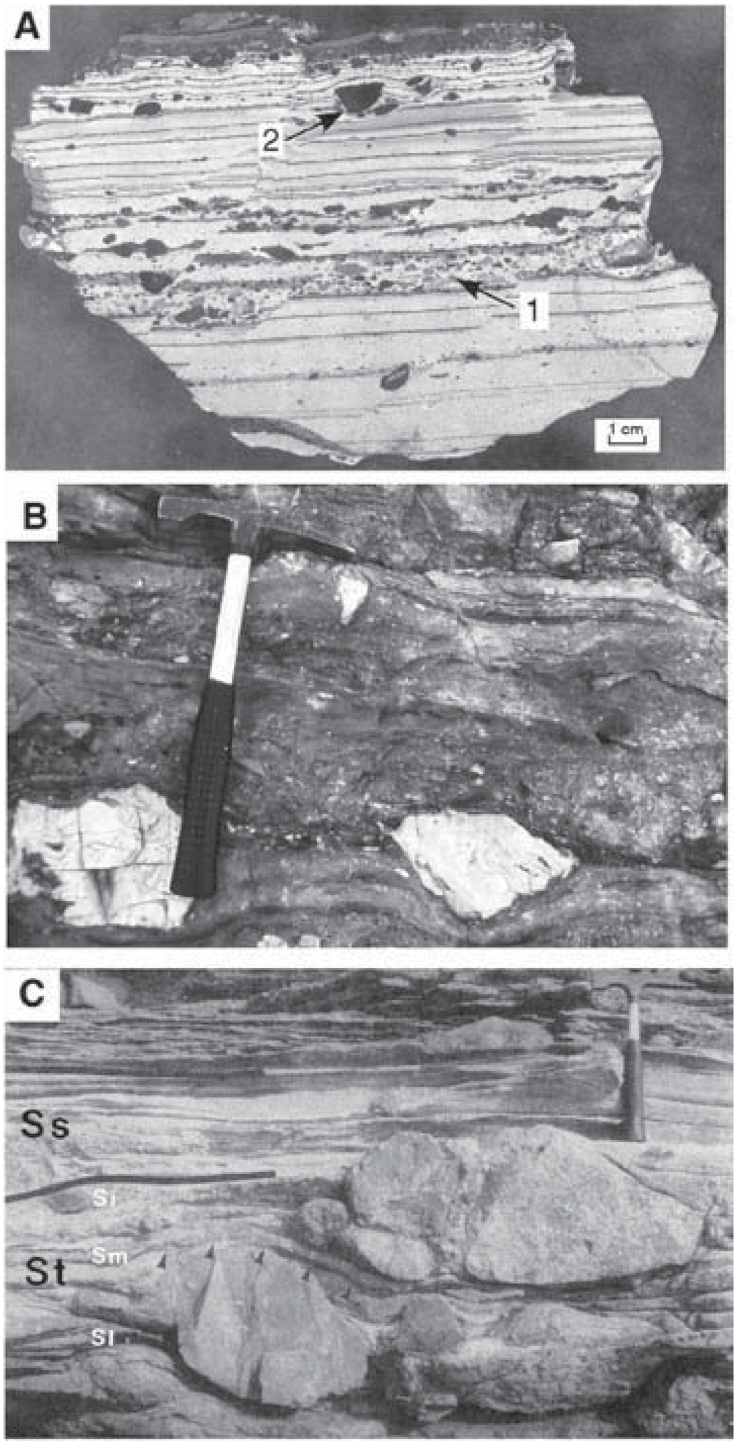
Conclusion. The breakup of Rodinia and the fragmentation of extensive carbonate platforms resulted in an enormous global flux of coarse and fine clastic carbonate to Neoproterozoic rift basins (Sections 3.3 and 4.1.4). Consequently, the simple stratigraphic association of carbonate deposits with so-called 'glacials' has no paleoclimatic significance because the carbonate is clastic in origin. The supposed close temporal and genetic relationship between primary carbonate strata and 'glacials' has not yet been adequately demonstrated. Coarse clastic debris can be readily explained as fault scarp talus and landslide debris recording uplift, faulting and cannibalization of older carbonate platform strata. Given the brutal 'postglacial' greenhouse conditions invoked for the Neoproterozoic when global temperatures are argued to have exceeded 50 °C, and the tectonic setting of active rifting, one would expect significant volumes of evaporite deposits to have accumulated in restricted or enclosed basins. Under such conditions, evaporates should be present, but this is not the case.

An instantaneous 'switch' in global climate, from glacial to postglacial conditions, is not supported by the Neoproterozoic stratigraphic record. 'Cap carbonates' held to record postglacial sea-level rise and precipitation from carbonate enriched oceans, are separated from underlying 'glacials' by unconformities or considerable thicknesses of marine strata such as turbidites. The question arises whether newly formed rift basins were enclosed or partially enclosed and thus representative of global geochemical conditions. We suspect that many 'cap carbonates' overlying diamictite facies are turbidites composed of fine-grained, recycled *clastic* carbonate (Fig. 9H; Section 4.1.4.3) or shallow water *primary* carbonate facies deposited at a late stage of rifting when subsidence rates had decreased allowing platformal conditions to be established (see Section 5.1.3.3). Neither can a direct glacial origin be assumed for underlying coarse-grained synrift strata.

3.9. Lonestones are ice-rafted dropstones and record glaciers at sea level

Debris can be rafted by icebergs and by ice that forms in seasonally cold but nonglacial climates (see Gilbert, 1990; Schermerhorn, 1977, 1981; Dionne, 1993; Eyles et al., 1998; Crowell, 1999). Evidence for Neoproterozoic glaciers reaching sea level is widely presented in the literature in the form of isolated clasts (*lonestones*) in fine-grained strata. In these cases, lonestones are interpreted as *dropstones* rafted offshore by floating icebergs (Hoffman et al., 1998a; Hoffman and Schrag, 2000; Condon et al., 2002). Clusters of clasts and matrix are also described as so-called 'till pellets' (Aitken, 1991a; Fig. 7A). Crowell (1999) illustrates several convincing examples from the Neoproterozic and other strata, but stresses the importance of those lonestones found in fine-grained deposits as indicators of floating ice. This emphasis is important. This is because, as we shall demonstrate below, 'outsized' lonestones are common within conglomeratic sediment gravity flow successions. Consequently, interpretation of a 'dropstone' origin simply on the basis of the presence of outsized clasts is not straightforward.

Large 'floating clasts' up to a few metres in size, together with 'clusters' and 'clumps' of clasts, have long been known to be carried within, and be deposited by, turbidity currents transporting poorly sorted sediment. This debris has no cold climate or glacial affinity (see, for example, Piper, 1970; Winn and Dott, 1979; Hein, 1982; Nemec and Steel, 1984; Mutti, 1992; Johansson and Stow, 1995; Kim et al., 1995; Lirer et al., 2001; Benvenuti, 2003). Postma et al. (1988) provided a detailed model for the transport of floating clasts along traction carpets within turbidity currents (see also Einsele, 2000; Postma, 1984). Nemec and Steel (1984) also presented a 'gravity-winnowing' model for the emplacement of outsized clasts in mass flow-dominated successions. Kim et al. (1995) emphasised that poorly sorted disorganised mass flows are frequently characterised by 'protruding clasts' that stick up above bed tops and which are draped by overlying beds, and 'loaded clasts' pressed into underlying finer-grained material (Fig. 7C). Mutti (1992) illustrates large 'floating boulders' and 'clusters of large clasts' in turbidites having settled down from subsequent hyperconcentrated flows, that are directly akin to 'ice-rafted clasts'. Jones and Desrichers (1992) described what he called 'dropstone type facies' within laminated facies interbedded with Mesozoic carbonate breccias that had been emplaced as 'floating clasts' within sediment gravity flows. Fig. 8A and B show a 'dropstone' in the decidely nonglacial late Miocene/early Pliocene Bidahochi Formation of Arizona, USA, where large boulders slid down the front of a lacustrine fan delta into fine-grained bottomset sediments.


A
2
1
1 cm
B
C
Ss
Sl
Sm
St
Sl

Depression of underlying laminations is clearly apparent. Fig. 8C shows similar 'dropstone-looking' boulders winnowed from debris flows moving across a modern alluvial fan near Las Vegas in Nevada.

The need to closely examine the origin of Neoproterozoic lonestones is because, in some cases, their interpretation as 'iceberg rafted dropstones' is the *only* evidence given for the presence of glaciers (and by extension that glaciers reached sea level). For example, in interpreting the Marinoan 'glacials' of the Ice Brook Formation of northwest Canada, Aitken (1991a, p. 34) stated that 'the argument for glacial influence rests primarily on the dropstones in laminated sediments interbedded with diamictite sheets'. Extending this supposition, Aitken (1991a, p. 34) simply interpreted associated diamictites as 'basal tills' although they are interbedded with deepwater turbidites in a marine rift basin. Aitken also highlighted the presence of 'till pellets' in shale. A good deal of attention has recently focussed on the 'dropstone horizon' (Figs. 5A,B,C and 7B) reported from the Chuos Formation of Namibia by Hoffman and Schrag (2000). Clasts are of local derivation but are interpreted as a record of the meltdown of global ice covers and dispersal of clasts by icebergs (see Section 4.1.4.3). In contrast, the reader should compare this outcrop, and the facies described by Aitken (1991a), with the 'outsize-clast-bearing sandstone' and 'disorganised conglomerate' facies described by Kim et al. (1995) from *non-glacial fan deltas* (Fig. 7B,C). As we have shown above, 'floating clasts' are common in sediment gravity flow successions. Other examples of mass flows containing large clasts misinterpreted as 'dropstones' were given by Eyles (1993, p. 82) in discussion of work on the Lynchburg Group of Virginia in which a glacial influence was recognised purely on the basis of the presence of outsized clasts (Wehr, 1986). The crudely bedded debris flows with outsized freighted clasts reported by Proust and Deynoux (1994; their Fig. 10.19) compare directly with the 'dropstone' horizon in Namibia. The latter, moreover, are part of a thick mass flow succession of debris flows (Section 4.1.4.1).

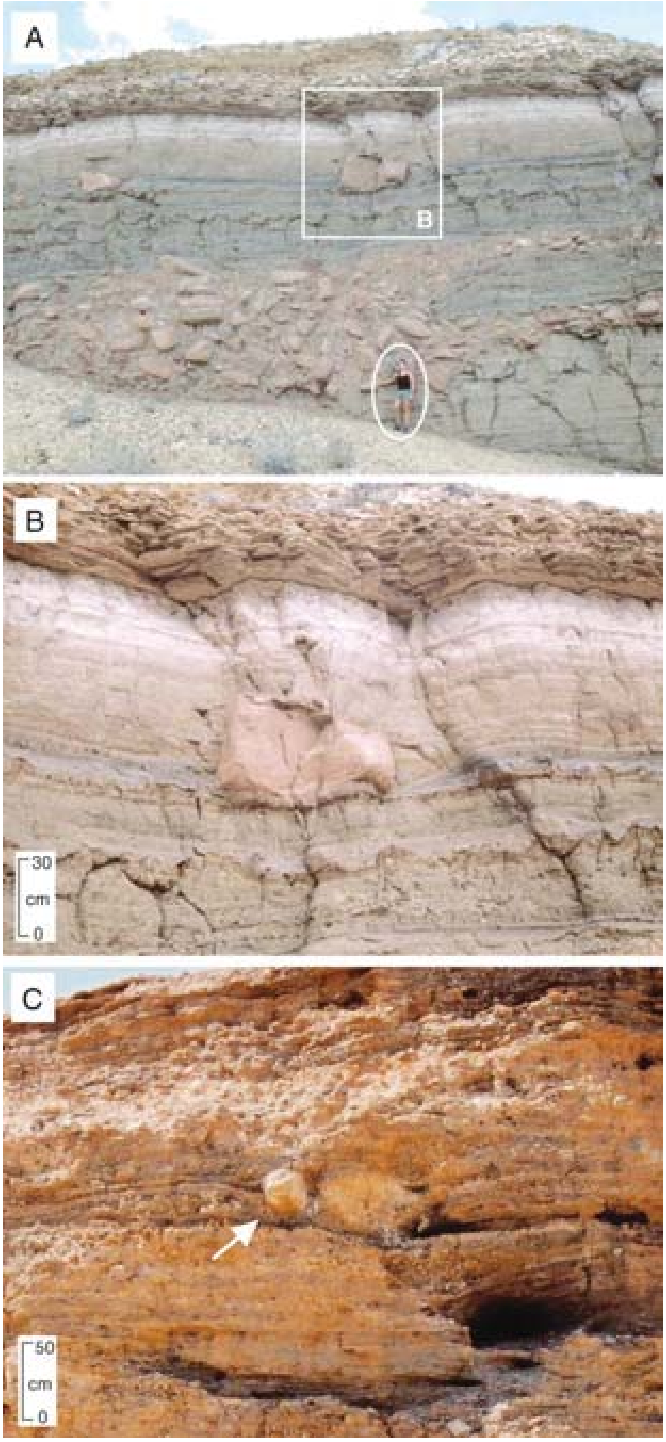
We note that Neoproterozoic 'ice-rafted debris' reported by Aitken (1991a), Hoffman et al. (1998a,b) and Condon et al. (2002) all occur in turbidites deposited on active slopes and interbedded with conglomeratic mass flows. It is precisely in this setting, where unstable slopes receive a wide range in particle sizes, that outsized lonestones occur as a consequence of the freighting processes described by Kim et al. (1995) and Postma et al. (1988). The 'till pellets' of Aitken (1991a) are likely clots of more cohesive matrix-rich debris entrained by dilute debris flows (see Kim et al., 1995; Fig. 7A).

As stressed by Crowell (1983), and clearly evident from studies of Pleistocene ice-rafted debris (Bond et al., 1992), icebergs carry debris far away from centres of glaciation into the deep ocean (or lakes). The supposed global marine reach of floating ice during one or more 'Snowball' events leads to the prediction that horizons of ice-rafted debris in fine-grained shales, containing far-travelled extrabasinal erratic lithologies, should be a widespread Neoproterozoic facies type. This appears not to be the case. Indeed, the glaciogenic Windermere Supergroup of northwest Canada provides an example of where deep marine facies that are laterally equivalent to the glacially influenced Rapitan Group *contain no ice rafted debris* (see Section 4.1.7.2). This supports a model of regional not global ice cover and a latitudinally restricted role for floating ice.

3.9.1. Conclusion

Outsize-clast-bearing deposits are by themselves, not a reliable indicator of a cold climate setting. Lonestones do not have a unique paleoenvironmental origin as iceberg-rafted dropstones because they are commonly produced as a consequence of sediment gravity flows. For this reason, we prefer use of the nongenetic term 'lonestone' for 'isolated oversized clasts in finer sediment with or without clear evidence of having been dropped from above' (Ojakan-

Fig. 7. (A) Lonestones reported as 'dropstones' (2) and thin, dilute debris flows reported as 'till pellets' (1) from the Marinoan Ice Brook Formation of Canada (Aitken, 1991a). (B) 'Dropstone unit' of Hoffman et al. (1998a,b) from the Ghaub Formation, Narachaamspos, Namibia. Compare with (C) outsize-clast-bearing sandstone facies of Kim et al. (1995). These outsized, so-called 'protruding', clasts originate from disorganised mass flows and closely resemble 'dropstones' of Aitken (1991a) and the 'dropstone unit' of Hoffman et al. (1998a,b; see also Fig. 5).


A
B
B
30
cm
0
C
50
cm
0

gas, 1985). Given the supposed worldwide reach of ice sheets and ice-covered oceans during one or more Neoproterozoic Snowball Earth events, globally travelled ice-rafted clasts of extrabasinal origin should be a very widespread component of the Neoproteroic sedimentary record. This does not appear to be the case.

3.10. Laminated fine-grained facies are seasonally deposited glaciolacustrine varvites

The notion that many Neoproterozoic fine-grained laminated facies are seasonally deposited glaciolacustrine varvites is long-lived (Sayles, 1919; Gevers, 1931) and is still seen in the continued use of 'varvite' as a descriptive term (see Hambrey and Harland, 1981; Hoffman et al., 1998b). Indeed, it has been common practice to ascribe any laminated argillite to a glaciolacustrine setting in keeping with the dominant interpretation of associated diamictites as terrestrial tillites (e.g., Spencer, 1971; Williams, 1988). Recognition of varvites in the early years of the last century were made against a background of intense interest in the derivation of late Pleistocene varve time scales (De Geer, 1926) using intercontinental 'teleconnections' of varve thickness as a record of climate variation, subsequently shown to be in error (e.g., Coleman, 1929). This thinking was long before the role of tidal processes, contour currents and sediment gravity flows was recognised in the formation of laminated and thin-bedded marine facies (Ghibaudo, 1992; Eyles, 1993, p. 22–25; Lowe and Guy, 2000; Mulder and Alexander, 2001). Schermerhorn (1974a) and Martin et al. (1985) stressed the need to consider the overall context of deposition as a guide to interpretation (e.g., marine vs. terrestrial) and the approach is still valid. The terms 'rhythmite' and 'laminite' are appropriate descriptive terms until any seasonal influence can be definitely determined.

3.10.1. Conclusion

Laminated fine-grained facies are deposited in many different depositional settings from terrestrial lakes to deep marine fans and slopes to shallow tidally influenced shelves and estuaries. Given that the Neoproterozoic record is dominated by marine strata, it follows that the widespread occurrence of seasonally deposited glaciolacustrine varves is unlikely.

3.11. Stratigraphic successions record major glacioeustatic fluctuations in sea level

In the absence of absolute age constraints throughout much of the Neoproterozoic, geologists have necessarily and understandably employed simple lithostratigraphic correlations from one continent to another (e.g., Sections 3.4 and 3.5). One such scheme involves recognition and correlation of so-called 'glacioeustatic successions' that are hundreds of metres (sometimes *kilometres*) thick. Such successions are defined by unconformity-bounded coarsening (or fining) upward trends (commonly called 'cycles') assumed to be the product of glacioeustatic sea-level fluctuations (e.g., Eisbacher, 1981, 1985; Christie-Blick et al., 1988; Aitken, 1989; Lindsay, 1989; Fairchild and Hambrey, 1995). For example, many Neoproterozoic diamictites are overlain by turbidites. Using the assumption that diamictites are terrestrial tillites, overlying facies are ascribed to postglacial glacioeustatic sea-level *rise* (Young, 1992a) similar to the interpretation made of 'cap carbonates' (Hoffman and Schrag, 2002; Section 3.8.2). Other workers claim to have found evidence of glacioeustatic *fall* in the form of incised valleys. These and their accompanying unconformities are interpreted as ravinement surfaces and canyons cut during glacioeustatic drawdown at the onset of widespread global glaciation (e.g., Christie-Blick, 1983, 1997; Christie-Blick et al., 1995; Edwards, 1984; Hoffman et al., 1998b; Sohl et al., 1999).

Having thus inferred that glacioeustatic fluctuations in sea level were a significant control on Neoproterozoic sedimentation, Young (1992a, p. 218) went further and suggested that 'temporal correlation of these rocks (possibly on a global scale) would then become a reasonable possibility'. This scheme

Fig. 8. (A, B) Lonestone emplaced in nonglacial fine-grained fan delta sediments, late Miocene/early Pliocene Bidahochi Formation, Arizona. (C) Lonestone emplaced by debris flow in modern alluvial fan deposits near Las Vegas, NV. These examples highlight how 'lonestones' can be emplaced by mechanisms other than floating ice. The presence of lonestones, interpreted as 'ice-rafted dropstones', has been used as evidence for Snowball Earth glaciation (Fig. 5).

was also employed by Young et al. (2001) and Ojakangas et al. (2001) with regard to global correlation of *Paleoproterozoic* glaciogenic diamictites. This practice echoes the widespread use of genetic 'sequence stratigraphy' among geologists where eustatic sea-level changes are seen as the principal control on accommodation of stratigraphic successions in sedimentary basins. In turn, sequence stratigraphy assumes that successions can be age-dated and correlated by reference to a global cycle chart depicting the ups and downs of sea level (e.g., Van Wagoner et al., 1988; Vail, 1992). The pitfalls and limitations of this approach have been reviewed at length by Miall (1997) and are not repeated here.

The principal problem with regard to recognition of glacioeustatic changes in Neoproterozoic strata is that much of the stratigraphic record was deposited in *active tectonic settings* (principally marine rift basins; Part III) during the initial breakup of Rodinia where sediment accommodation was controlled by the rate of *tectonic subsidence*. Under this tectonic setting, the stratigraphic record of eustatic sea-level fluctuation is partly or entirely suppressed by those changes in water depths (*relative* sea level) resulting from changes in tectonic subsidence rates and/or the rate at which sediment is supplied to the basin.

The major constraint on the Neoproterozoic 'glacioeustatic succession' model is that glacioeustatic fluctuations by themselves do not create accommodation space because absolute sea level always returns to its preglacial position after glaciation. Accommodation space can only be created by tectonic subsidence. Thus, the mere presence of thick stratigraphic successions above 'glacials' demonstrates ongoing subsidence and points to an overriding tectonic control on any change in relative water depths.

Another problem is that of the *magnitude* of glacioeustatic sea-level changes inferred by some workers. The simulation of Hyde et al. (2000) with reduced solar luminosity and decreased CO_2 levels produces ice-covered portions of Rodinia with a total ice volume no more than during the Last Glacial Maximum in the Pleistocene some 20,000 years ago. Such an ice volume resulted in geologically brief reductions in Pleistocene eustatic sea levels of about 150 m. This should be contrasted with so-called 'glacioeustatic' successions that are hundreds of metres in thickness (e.g., Windermere Supergroup of northwest Canada; Eisbacher, 1985; Young, 1992a).

Possible small-scale changes in sea level likely conditioned by glaciation have been identified from the mid-Neoproterozoic Chuar Group of southwestern North America (Dehler et al., 2001). Eustatic data from the Chuar Group suggest the initial growth of ice covers just before 740 Ma and are of considerable importance as they confirm that glaciation was progressive (and likely regional) and did not involve instantaneous global refrigeration. Other glacioeustatic changes appear to be recorded in the Fiq glacials of Oman (Leather et al., 2002).

3.11.1. Conclusion

Interpretation of thick Neoproterozoic successions as a direct product of glacially driven global changes in sea level fails to recognise the active tectonic setting of sedimentation. Under these conditions, long-term changes in water depths are driven by variation in subsidence rate not eustatic sea level. This questions the application of 'sequence stratigraphic' concepts as a tool for global correlation in the Neoproterozoic based on glacioeustatic fluctuations in sea level. The limitations of the classical sequence stratigraphic approach identified above weakens employment of so-called 'glacioeustatic sequence boundaries' as a Global Stratotype Section and Point (GSSP) for the terminal Proterozoic system based on assumed worldwide synchronicity of glaciation (e.g., Christie-Blick et al., 1995, p. 21).

3.12. Carbon isotope chemostratigraphy indicates global permafrost

Variation in C-, S- and Sr-isotopic compositions in Neoproterozoic carbonate strata are distinguished by being much greater than those of the Phanerozoic (e.g., Kaufman and Knoll, 1995; Fig. 9). Proponents of the Snowball Earth attribute this to global refrigerations. They suggest that extreme climatic fluctuations and the resulting shutdown in global biological activity are recorded by $\delta^{13}C$ isotope excursions. Preglacial $\delta^{13}C$ values are used as a proxy to infer a healthy biotic environment. Prior to the onset of glaciation, $\delta^{13}C$ values plummet to levels equivalent to a primary volcanic source and are attributed to a massive reduction in biological activity in response to global refrig-

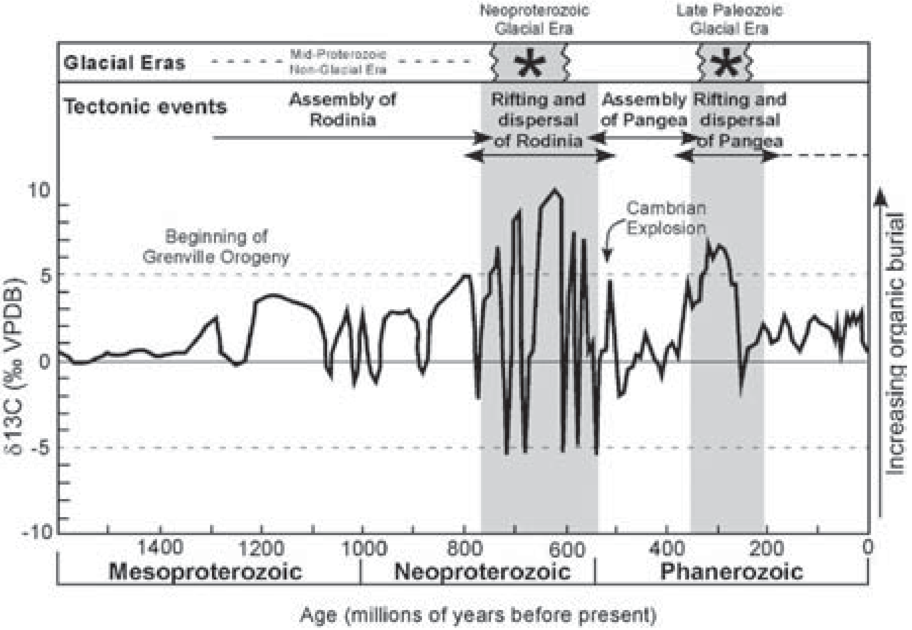
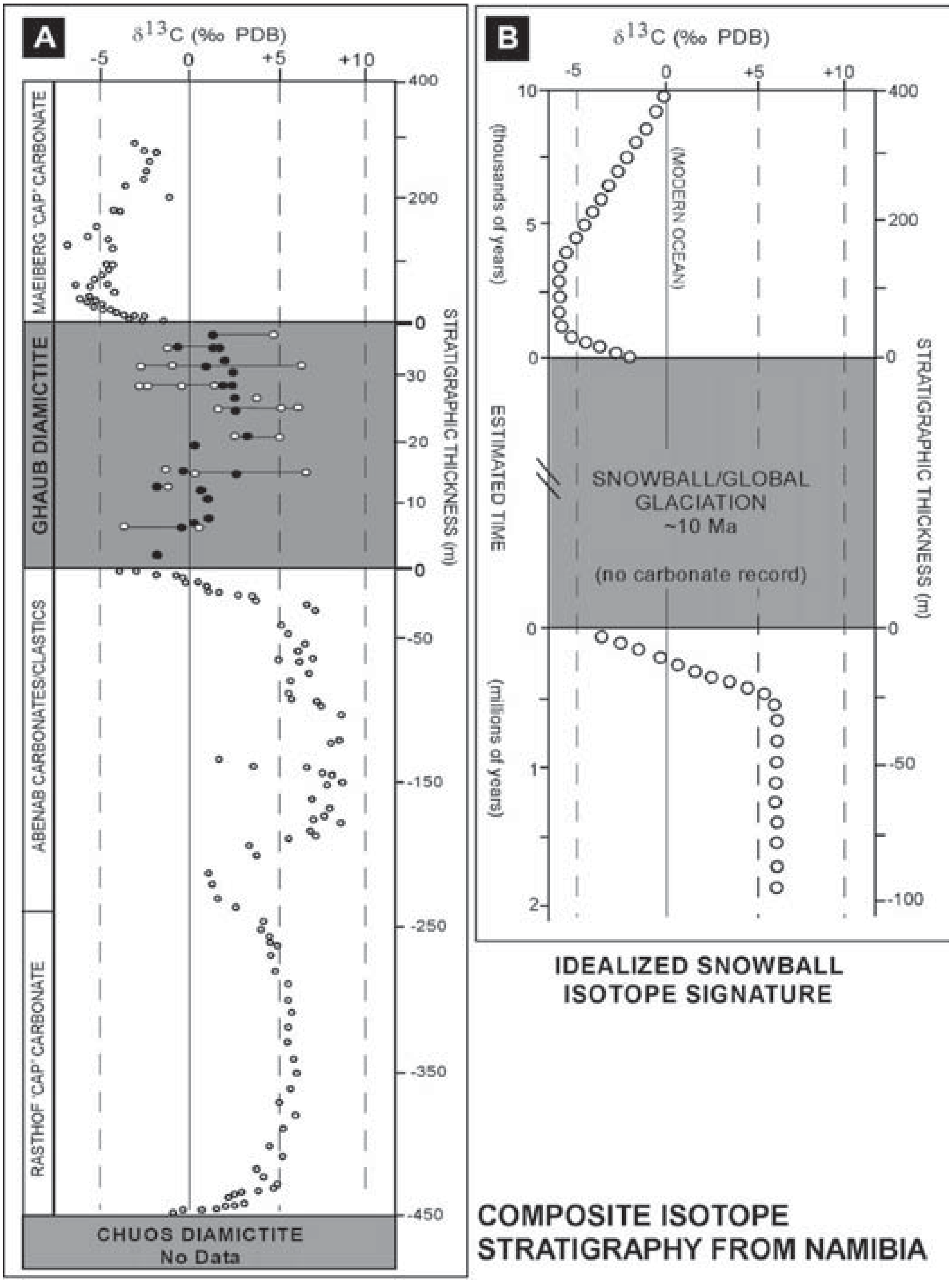


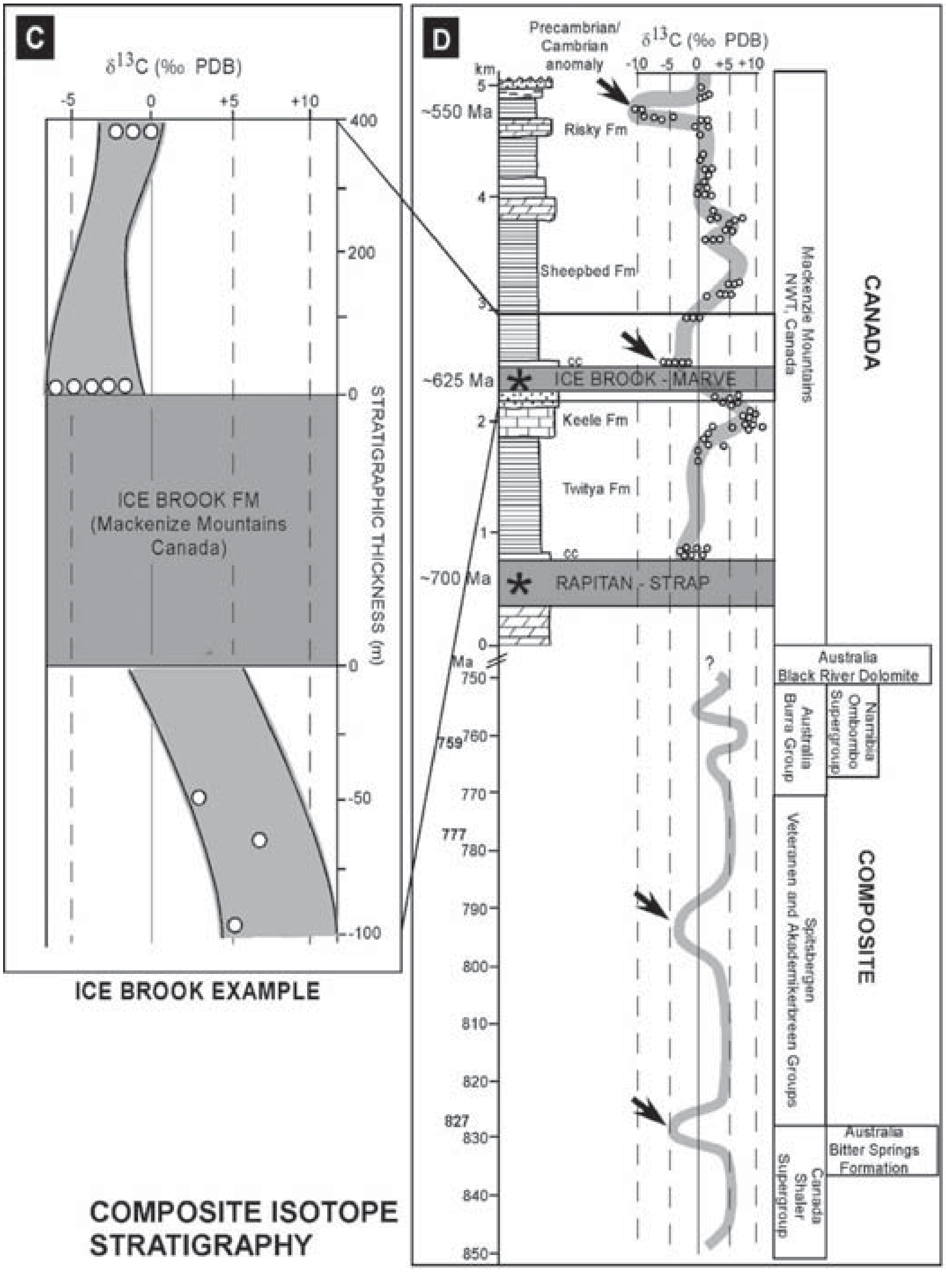
Fig. 9. Glacial eras and carbon isotope variation in the context of global tectonic cycles of supercontinent assembly and breakup. Supercontinent rifting appears to be associated with prominent carbon isotope excursions reflecting increased burial of organic carbon in newly formed and rapidly subsiding rift basins. Modified from Hoffman and Schrag (1999) and Kaufman (1997).

eration. So-called 'cap carbonates' deposited after the snowball event record a continuation of negative $\delta^{13}C$ values that slowly become more positive hundreds of metres upsection (Fig. 10B). This geochemical signature suggests that a Snowball Earth had a catastrophic effect on Neoproterozoic biota and was followed by the slow recovery of organisms in the aftermath.

The characteristic Snowball $\delta^{13}C$-isotopic trend (Fig. 10B) has been identified in northern Namibia (Hoffman et al., 1998b; Saylor et al., 1998; Fig. 10A), Australia (Kennedy, 1996; Hill and Walter, 2000), the US (e.g., Death Valley, Prave, 1999; Abolins et al., 2000) and northwest Canada (Narbonne et al., 1994; Fig. 10C,D), suggesting a common global isotopic response. Naturally, this is dependent on correlation of broad isotopic trends from one area to another (e.g., Kaufman and Knoll, 1995) and the strength of the assumption that deposits accumulated synchronously. This can be challenged (Shields et al., 2002; Section 3.5). Recent global correlations of isotope variation, presented by Hoffman and Schrag (2002, their Fig. 8), show *precise* correlation of both stratal thicknesses *and* isotope variation between outcrops in northwest Canada (Rapitan-Ice Brook) and Namibia (Chuos–Ghaub). If correct, these correlations are truly significant because they indicate that rates of subsidence and deposition were exactly the same in the two widely separated basins.

Fig. 10. (A) Composite carbon isotope stratigraphy from Namibia after Hoffman and Schrag (1999) and Kennedy et al. (2001a); open circles are from clasts, closed circles from matrix from diamictites of the Ghaub Formation. Note considerable variation. (B) Idealized carbon isotope trend pre- and post-Snowball glaciation (Hoffman and Schrag, 1999). (C) Carbon isotope results from strata above and below the Ice Brook Formation, Mackenzie Mountains, northwest Canada (Fig. 12B,D; modified from James et al., 2001). Note coarse spacing of samples and their inferred "Snowball trend". (D) Composite carbon isotope stratigraphy between 850 and 550 Ma for Canada, Australia and Spitsbergen (from James et al., 2001; Narbonne et al., 1994; Hill and Walter, 2000). Note that negative isotopic excursions often occur stratigraphically well before putative glaciations (see also Hoffman and Schrag, 2002; their Fig. 8). Four other "Snowball-like" negative excursions are arrowed, but no geographically widespread glacial deposits are known at these times suggesting tectonic or other controls (Fig. 9).


A
δ13C (‰ PDB)
-5
0
+5
+10
400
200
0
30
20
10
0
-50
-150
-250
-350
-450
STRATIGRAPHIC THICKNESS (m)
MAEIBERG 'CAP' CARBONATE
GHAUB DIAMICTITE
ABENAB CARBONATES/CLASTICS
RASTHOF 'CAP' CARBONATE
CHUOS DIAMICTITE
No Data
COMPOSITE ISOTOPE STRATIGRAPHY FROM NAMIBIA
B
δ13C (‰ PDB)
-5
0
+5
+10
10
5
0
0
1
2
400
200
0
0
-50
-100
(thousands of years)
(MODERN OCEAN)
ESTIMATED TIME
SNOWBALL/GLOBAL GLACIATION
~10 Ma
(no carbonate record)
(millions of years)
STRATIGRAPHIC THICKNESS (m)
IDEALIZED SNOWBALL ISOTOPE SIGNATURE


C
δ13C (‰ PDB)
-5
0
+5
+10
400
200
0
-50
-100
STRATIGRAPHIC THICKNESS (m)
ICE BROOK FM
(Mackenize Mountains
Canada)
ICE BROOK EXAMPLE
D
Precambrian/
Cambrian
anomaly
δ13C (‰ PDB)
-10 -5 0 +5 +10
km
5
4
3
2
1
0
~550 Ma
~625 Ma
~700 Ma
Risky Fm
Sheepbed Fm
cc
ICE BROOK - MARVE
Keele Fm
Twitya Fm
cc
RAPITAN - STRAP
Mackenzie Mountains
NWT, Canada
CANADA
Ma
750
759
760
770
777
780
790
800
810
820
827
830
840
850
?
Australia
Black River Dolomite
Australia
Burra Group
Namibia
Ombombo
Supergroup
Spitsbergen
Veteranen and Akademikerbreen Groups
COMPOSITE
Australia
Bitter Springs
Formation
Canada
Shaler
Supergroup
COMPOSITE ISOTOPE
STRATIGRAPHY

Under closer scrutiny, the Neoproterozoic isotope record from different locations indicates considerable variability (see Brasier et al., 1996a,b; Shields et al., 2002). Most significantly, the isotopic record indicates *several* possible 'Snowball events' in the absence of any associated sedimentary record for the supposed climatic changes (e.g., Corsetti and Kaufman, 1999; Kennedy et al., 1998; Fig. 10D). Hill and Walter (2000) identified this enigmatic situation in regard to several Neoproterozoic intervals of low C-isotope values in Australia unrelated to any record of glaciation. Shields (1999) demonstrated that anomalously low C-isotope values from so-called 'postglacial carbonates' are identical to seawater values from the early Cambrian that again, are not associated with glaciation nor faunal extinctions. He concluded that other factors that might result in lower seawater C-isotope values have been overlooked. The question thus arises as to whether there is sufficient knowledge of the full range of secular variation in isotopes particularly at a time of enhanced tectonic activity during the rifting of Rodinia and enhanced sea floor spreading. This issue has been raised by Sochava and Podkovyrov (1995) with regard to the composition of Neoproterozoic dolomites and limestones; they point out that during the rifting of Rodinia (their Pangea I), over 20,000 km of new passive margin and volcanic spreading centres were formed over a very brief time interval. The rapid burial of organic matter in rapidly subsiding basins during supercontinent breakup may explain some isotope variation (Fig. 9).

In general, the sampling interval used in studies of Neoproterozoic 'glacial' successions is coarse (typically 1 sample every 3–100 m of stratigraphic thickness, e.g., Fig. 10C). The presence of hiatuses and the inability to sample siliclastic facies hides additional secular variation in isotopes. For these reasons alone, it is very unlikely that studies have captured the full range of isotopic variation. As a case in point, Kennedy et al. (2001a, their Fig. 1) conducted very close sampling of the glacial interval in Namibia and detected a clear trend in isotopic values *within* tillite (Fig. 10A). This is certainly not to be expected in a supposed tillite formed as a result of subglacial erosion, mixing and homogenisation of preexisting debris; instead, systematic vertical geochemical variation supports the contention that such facies are glacially influenced *marine* rocks and accumulated through time on a sea floor. In addition, these workers also identify positive $\delta^{13}C$ values from within glacial deposits and 'cap carbonates' in Namibia and the Amadeus Basin that cannot readily be explained by a near-abiotic ocean predicted by the Snowball model (Kennedy et al., 1998, 2001a).

Other mechanisms have been proposed to explain negative carbon isotope excursions and include postglacial sea-level rise and upward movement of the oxygen-minimum zone (Watanabe, 2001; Hoffman and Schrag, 2002), the release of gas hydrates (Kennedy et al., 2001b), and meteorite impact and regional metamorphism and fluid–rock interaction (Labotka et al., 2000). Turner (1982) suggested that slightly more negative carbon isotope values are consistent with slight fractionation of normal atmospheric CO_2 due to carbonate precipitation. A detailed review is beyond the scope of this paper, but in this regard, it must be said that understanding of relatively recent *Phanerozoic* geochemical fluxes and their relationship to climate change is limited. Boucot and Gray (2001) provide a very useful review of the relationship between tectonics and atmospheric CO_2 pointing out complexities and uncertainties that apply equally to the Proterozoic record. A recent isotopic study from the Mackenzie Mountains of northwest Canada (James et al., 2001) also highlights uncertainty regarding simple interpretation of the isotopic record. They state that 'attributes of the Ice Brook cap carbonate and associated rocks suggest precipitation from a Neoproterozoic ocean not highly perturbed by global glaciation' (p. 1258).

Similar C-isotopic excursions, comparable in magnitude seen in the Neoproterozoic, are recorded in the late Permian at about 250 Ma (Fig. 9). To explain these younger events, Knoll et al. (1996) invoke the same 'glaciation dependent' model as employed for the Neoproterozoic. However, the available sedimentary evidence indicates only minimal global ice covers during the late Permian with seasonally produced sea ice recorded in Siberia (Crowell, 1999). Final deglaciation of Carboniferous–Permian ice sheets of the southern Gondwana continents had already occurred. This indicates that extensive glaciation cannot be the prime cause of unusual secular variations in C-isotopes in the late Permian and we suggest a similar finding in regard to the interpretation of Neoproterozoic excursions.

Investigation of strontium isotopes has also questioned assumptions behind the Snowball model. The reported shift in marine $^{87}Sr/^{86}Sr$ values to more continental values during the Marinoan glaciation points to an increase in continental runoff (Kennedy et al., 2001a). This shift is consistent with glacial erosion of exposed continental crust, but is contrary to the Snowball model that requires the hydrologic cycle, and therefore continental runoff, to completely cease during global glaciation. Kennedy et al. (2001a) argue therefore that it is difficult to accommodate both the strontium- and carbon-isotopic data simultaneously in the Snowball model (see also James et al., 2001). In particular, the $^{87}Sr/^{86}Sr$ isotope record fails to support the putative increase in silicate weathering rate needed to produce the thick cap carbonate in the Snowball model. Carbonate weathering may have buffered the strontium signal, causing it to appear relatively invariant, but as Kennedy et al. (2001a) point out, this would require a carbonate to silicate weathering rate >9:1 which in turn, would reduce the influence of silicate weathering on atmospheric carbon-isotopic composition.

3.12.1. Conclusion

Despite the limitations of the C-, S-, and Sr-isotopic records from the Neoproterozoic, the *magnitude* of isotopic variation in such strata is unusual and with the exception of the late Permian far exceeds those recorded subsequently in Phanerozoic strata. It appears likely, based on a rapidly growing chemostratigraphic database, that *some* excursions are primary and global in extent. Given that the sedimentologic and stratigraphic records do not support the hypothesis of global 'Snowball' glaciations, it can be concluded that such shifts are not primarily determined by glaciation and that other causal mechanisms should be sought (Fig. 9).

The Neoproterozoic saw the protracted rifting of a large supercontinent (Rodinia) that initiated a massive transformation of the planet's geography. In our opinion, the effects of global 'megarifting' on isotopic and geochemical fluxes in newly formed oceans should be more closely evaluated. Simple attribution of C-isotopic fluctuations to putative global ice covers and permafrozen continents is not supported by the stratigraphic record of glaciation and by sedimentological evidence for an active hydrological cycle. Evidence is reviewed below that extends this finding to the biological record.

3.13. Biological record indicates global permafrost

The Precambrian–Cambrian boundary broadly separates fossils from two distinct evolutionary phases: the soft-bodied Neoproterozoic Ediacaran biota and the shelly Cambrian faunas. Initially, this biological change is thought to have resulted from mass extinctions created by successive 'freeze–fry' Snowball events that 'annihilated most kinds of eukaryotic life...except bacteria' (Runnegar, 2000). The argument goes that extreme glacial conditions would also have provided the evolutionary stress (an 'intense environmental filter'; Hoffman et al., 1998b, p. 1346) thereby inducing the necessary biotic 'fitness' required by organisms to survive brutal hothouse conditions that would come in the aftermath of the snowball. This process, repeated as part of several 'global megaevents' (Hoffman, 2002), is viewed as an accelerant of evolutionary rates promoting the spawning of metazoans (Hoffman et al., 1998b, p. 1135–1136; Hoffman and Schrag, 2002, p. 74).

In contrast to the hypothesis outlined above, there appears to be no clearly demonstrated relationship between Neoproterozoic glaciations and changes in the fossil record sufficient to support the case that global refrigeration was the *key* stressor on biological evolution (Bengsten, 1994; Kaufman and Knoll, 1995; Hallam and Wignall, 1997; Brasier and Lindsay, 2000; Grey et al., 2003). Investigation of Ediacaran biotas in Cambrian rocks indicates that faunal changes were *gradual* through the Precambrian–Cambrian transition (Grotzinger et al., 1995; Watanabe, 2001). This is significant because Ediacaran organisms were immobile, perhaps lichenlike organisms with maximized external surfaces making them highly sensitive to environmental change (Retallack, 1994). Most lived in shallow, likely euphotic settings between fair-weather and storm-wave base (Narbonne, 1998). Ediacara-type fossils occur *above* Neoproterozoic glacially influenced marine deposits in the Avalonian Conception Group in eastern Canada and the Windermere Supergroup in northwestern Canada (Narbonne and Hoffman, 1987; Narbonne, 1998;

Gehling et al., 1999; Dalrymple and Narbonne, 1996; MacNaughton et al., 2000). In the Mistaken Point Formation, Ediacara-type fossils of eastern Canada were dated using U–Pb zircon techniques to 565 Ma (Benus, 1988) which is much younger than similar fossil assemblages in Namibia (Grotzinger et al., 1995) and the White Sea (Martin et al., 2000) and postdates by a large margin the main phases of Neoproterozoic glaciation. Given the environmental 'sensitivity' of Ediacaran organisms, their stratigraphic position both below and above Neoproterozic glacials would appear to rule out global permafrost and the cessation of hydrologic activity as the main stressor on Ediacaran organisms.

According to Narbonne and Gehling (2003), the Ediacaran fauna of the Mistaken Point Formation in Newfoundland 'give a first glimpse of complex megascopic life after the meltdown of Snowball Earth glaciers'. It is worth noting that the fauna occurs 1.5 km above the Gaskiers Formation making any close temporal relationship tenuous. Moreover, the 'glacials' of the Gaskiers Formation are deep marine in origin and likely record local ice centres on volcanoes and the shedding of predominantly volcaniclastic sediment into deep water as turbidity flows and debris flows (Section 4.1.7.5). Any glacial influence on the marine environment was weak; a volcanic influence was more significant as Ediacaran fauna in Newfoundland are preserved in tuffs.

Eukaryote microfossils are found in rocks that both predate and postdate supposed Snowball events and provide firm evidence for eukaryote survival uninterrupted by 'Marinoan global glaciation'. Proponents of the Snowball model attribute this to the presence of refugia such as near-surface hot springs and volcanic fields. They propose that organisms adapted to live under extreme conditions such as around hydrothermal vents in the modern oceans and the Dry Valleys of East Antarctica. James et al. (2001, p. 1258) refute this model.

The Neoproterozoic *achritarch* record affords an additional test of the Snowball Earth model because it contains shallow water marine types most susceptible to catastrophic climate changes. Grey et al. (2003) examined the phytoplankton record for the Australian Neoproterozoic based on a study of almost 2000 samples from 30 drillholes through pre- and post-Marinoan glacial strata in the Adelaide Rift Complex, Officer and Amadeus basins. Two palynofloras were recognised independent of sedimentary facies; an Ediacaran Leiosphere-dominated palynoflora (ELP) and a younger Ediacaran Complex Acanthomorph-dominated palynoflora (ECAP). The ELP palynoflora is of great significance because it contains those forms most susceptible to climatic change because they are mostly simple leiospheres and filaments living in shallow water shelf environments most at risk from global glaciation. In fact, preglacial and postglacial achritarch populations are almost identical consisting of morphologically simple and long ranging forms some of which extend back to the Mesoproterozoic. They do not indicate repopulation of marine areas by phytoplankton types such as extremophiles that survived catastrophic glaciation in hot spring or glacial refugia (see also Mendelson and Schopf, 1992).

According to Grey et al. (2003), the change from ELP to ECAP palynofloras is abrupt at all sites and ascribed to a significant evolutionary change that occurred some 20 million years *after* Marinoan glaciation and coincident with the Acraman impact event ca. 580 Ma. Stratigraphically, this event occurs during deposition of the Bunyeroo Formation in the Adelaide Rift Complex. Diversification is the response to environmental recovery following a massive bolide impact not glaciation (K. Grey, personal communication, 2000, 2001). Other workers have argued that enhanced tectonic subsidence and sediment accommodation as Gondwana amalgamated during the Early Cambrian Pan-African orogeny have distorted the record of Cambrian radiations making them appear abrupt and stepwise (Brasier and Lindsay, 2000).

3.13.1. Conclusion

In regard to many types of organisms, the Neoproterozoic biological record does not show clear and unambiguous evidence of the global biotic crises that have been attributed to one or more severe global glaciations by the Snowball Earth model. There is no support for a temporal or causal link between global deglaciation and the Cambrian 'explosion'. The late Neoproterozoic was a time when the Earth's geography experienced dramatic first-order changes resulting from the breakup of Rodinia. In turn, this was followed by Early Cambrian amalgamation of Gondwana. Both processes created vast areas of new habitat and ecological niches. Consequently, a combination of causes, not a single simple glacial 'trigger', likely played a role in early Phanerozoic radiations.

3.14. Statement of findings of Part I

The 'Snowball Earth' hypothesis makes many assumptions regarding the nature of the Earth's sedimentological, stratigraphic, geochemical, biological, and geophysical record that cannot be supported. Specifically, ongoing uncertainty surrounds interpretation of key sedimentological, paleomagnetic and geochemical data from Africa and Australia purposing to record low latitude snowball conditions.

4. Part II: the stratigraphic record of Neoproterozoic glaciations

4.1. Glaciation and Rodinian megarifting

What follows is a review of the published Neoproterozoic glacial record emphasising tectonic settings and paleoenvironments. For simplicity in presenting such information, we make the simple chronological assumption that deposits cluster into two principal time horizons (Sturtian and Marinoan) that are genetically related to the megarifting of Rodinia and the breakout of Laurentia. We cannot emphasise very strongly that this bipartite division is strongly simplistic given that rifting was likely diachronous along rifted continental margins that extended over more than 40° of latitude. Clearly, the use of any one reconstruction of Rodinia is fraught with difficulties because the configuration of Rodinia varies from one worker to another (e.g., SWEAT reconstruction, Moores, 1991; Hoffman, 1991; Dalziel, 1991, 1997; AUSWUS; Karlstrom et al., 1999; Li et al., 1996; Li and Powell, 2001; AUSMEX; Wingate and Giddings, 2000; Wingate et al., 2002, and those of Weill et al., 1998; Hartz and Torsvik, 2002). There is no broad consensus as to when and where the component parts of Rodinia were ultimately assembled nor broke apart. As a consequence, the reconstructions used here in Fig. 4 are simplistic. Their primary purpose is to identify the very different geographic locations across Rodinia, particularly Laurentia, where rifting occurred between 750 and about 610 Ma, and where *a definite glacial imprint on sedimentation can be identified.*

4.1.1. STRAP: first phase of Rodinian rifting and the circum paleo-Pacific (Sturtian–Rapitan) glaciation ca. 750 Ma

The oldest phase of Neoproterozoic glaciation is classically represented by the Sturtian of Australia, the Sinian of south China and the Rapitan Group of northwestern Canada (termed here STRAP), and occurs at the base of thick 'supersequences' that record rifting and subsidence of grabens accompanying the initial breakup of Rodinia. At this time, Australia–Antarctica separated from *western* Laurentia to form the paleo-Pacific Ocean sometime after 750 Ma (Fig. 4A; Powell et al., 1994). Direct stratigraphic comparison between rift successions in the Adelaide Rift Complex, northwestern North America and China has been proposed (Eisbacher, 1985; Young, 1995). At this time, the breakup of Rodinia not only severed Australia from Laurentia, but also resulted in the Australia being traversed by a large triple junction (Fig. 4A).

4.1.2. MARVE: second phase of Rodinian rifting; circum-Iapetus Ocean (Marinoan–Vendian) glaciation ca. 610 Ma

The youngest Vendian glacial record (in the circum Atlantic region of northwest Europe) is also dominantly preserved in rift basins that are related to a second phase of Rodinian rifting some time around 610 Ma. This youngest phase occurred when Baltica separated from the *eastern* margin of Laurentia to form the paleo-Atlantic Ocean (Iapetus Ocean) and when the North China Block moved away from Siberia (Fig. 4B). Glacially influenced rift-related deposits of Scotland, Greenland, Scandinavia and China belong to this group and are broadly equivalent to the Marinoan of Australia. We use the term 'MARVE' for this Marinoan–Vendian group. This phase of Rodinian breakup is reasonably well constrained in age by the voluminous 650 Ma Egersund tholeiitic dikes of southwest Norway which have been attributed to early rifting initiated by a mantle plume (Torsvik et al., 1996; Bingen et al., 1998). Rift-related dikes also occur in eastern Laurentia such as the Long Range dikes of southern Labrador which are dated at about 615 Ma; Torsvik et al. (1996) and Hartz and

Torsvik (2002) suggested that rifting along the eastern Laurentian margin proceeded diachronously from present day north to south until 550 Ma (Cawood et al., 2001).

4.1.3. Northwest Africa

Convincing sedimentological evidence of a Marinoan-age (or younger) terrestrial ice sheet covering much of a large Neoproterozoic foreland basin occurs in glacial strata preserved across the extensive Taoudeni Basin (2×10^6 km^2) of the West African craton (Proust and Deynoux, 1994). These strata are highly significant in several regards. First, they contain undoubted terrestrial sediments such as tillites. Second, they record uplift associated with Pan-African collisional events. Uplift and subsequent regional climate cooling occurred in mid-to-high latitudes prior to long-term subsidence of the foreland basin. The demonstrated relationship between tectonics and climate change does not require global ‘Snowball’ conditions.

Outcrops of glaciogenic deposits have been correlated around the circumference of the basin such as the variably named Jbeliat Group (Deynoux and Trompette, 1981; Deynoux et al., 1991), the Bakoye Group (Proust et al., 1990; Proust and Deynoux, 1994) and the Bthaat Ergil Group (Trompette, 1994). Moussine-Pouchkine and Bertrand-Sarfati (1997) presented new structural and age data from the northern basin margins of Mali and Algeria and argued that the basin fill could be divided into four ‘tectonosedimentary subdivisions’ (Douik-Hank, Dar Cheikh, Cheikhia, Azlaf-Guettatira). Well-studied glaciogenic deposits (Fersiga Formation) occur in the uppermost Guettatira subdivision. They rest unconformably on folded and faulted strata marking Pan-African Orogeny and broad uplift of the West African shield. They are no older than 620 Ma and no younger than 595 Ma (Moussine-Pouchkine and Bertrand-Sarfati, 1997). Unusually, a direct terrestrial record of glacial and periglacial environments has been preserved including aeolian deposits (Deynoux et al., 1989). Glacial strata form the lowermost part of a ‘triad’ of overlying shallow water carbonates (with diagenetic barite; the Oued Djouf Formation) and shales (e.g., Azlaf Group) that are up to 1000 m thick record long-term subsidence of the West African Shield in response to collision and crustal thickening. Better age data are needed and this necessarily constrains interpretation of paleomagnetic data which suggest deposition in moderate to high latitudes (Evans, 2000, p. 398). Glacial sedimentation occurred in the context of a collisional foreland basin setting related to Pan-African I orogeny; orogenically related, nonglacial diamictites of Northwest Africa are reported by Hefferan et al. (1992), Eyles (1993) and Evans (2000).

4.1.4. Southern Africa

Outcrops in Namibia are still poorly known, but are of fundamental importance to the reconstruction of Neoproterozoic paleoclimates as they represent the *key outcrops* for the postulated Snowball Earth. It is from Namibia that stratigraphic evidence for the model was first presented by Hoffman et al. (1998b) and forms the basis of its adoption elsewhere. Southwest Africa contains several Neoproterozoic stratigraphic units that record continental rifting and separation as Rodinia broke up after 750 Ma. They are preserved within the so-called Damara Belt that partly encircles the Congo craton. Work by Hoffman et al. in Namibia has focussed on two ‘glacigenic’ formations (Chuos and Ghaub) that are widely exposed along the southern margin of the Congo craton (Fig. 6). It is widely assumed that these formations are equivalent in age to Sturtian and Marinoan, respectively.

4.1.4.1. Chuos Formation of Namibia. The oldest and thickest of the Namibian ‘glacials’ (Chous Formation) contains prominent diamictite units named after extensive outcrops in the Chuos Mountains of the Damara Belt. Diamictite units are as much as 800 m thick and were mapped as ‘basal moraine’ by Gevers (1931), Le Roex (1941) and Smith (1965). Gevers referred to the ‘Chuos Tillite’ and subsequent workers correlated this in traditional homotaxial ‘like with like’ fashion with other similarly thick ’boulder-bearing schists’ in southern Africa (De Kock and Gevers, 1933; Martin, 1965; Kröner and Rankama, 1972). The Chuos Tillite is a key stratotype for one or more ‘Snowball Earths’ (Hoffman et al., 1998b, 1999; Corsetti and Kaufman, 1999; Halverson et al., 1999; Kennedy et al., 2001a) and its origin as a record of continental glaciation is widely assumed.

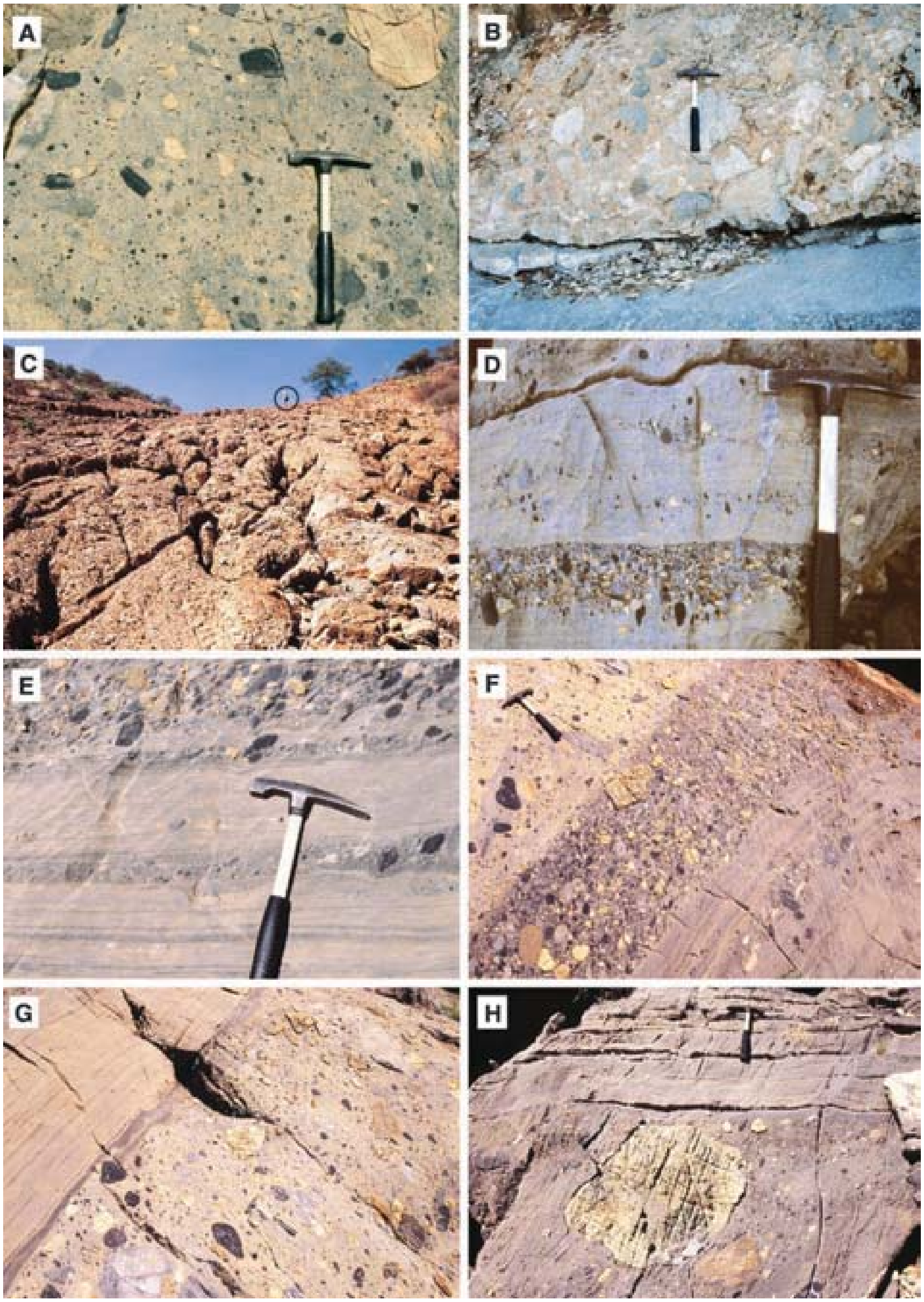
Results of a lengthy and detailed reexamination of the Chuos Formation ‘glacials’ were presented by

Martin et al. (1985) acting in response to objections to a terrestrial glacial origin raised by Schermerhorn (1974a, 1975). Martin et al. (1985) recognised that diamictites are interbedded with turbidites, slump breccias and olistostromes and ascribed all these to submarine mass flows within a broad rift zone. Significantly, he and others (Porada and Wittig, 1983) recognised that diamictites did not form continuous stratigraphic horizons, but are markedly localized along strike in response to diachronous deposition of mass flows and changing depocentres within the basin. Martin et al. (1985) identified a well-defined relationship between diamictite bed thickness and maximum clast size. Such a relationship is characteristic of debris flows and results from the enhanced competency of thicker flows to transport large boulders (e.g., Nemec and Steel, 1984). These data negate a simple origin for diamictites as glacial till and also remove any global chronostratigraphic significance. Furthermore, no definite source of glaciclastic debris could be identified by Martin et al. (1985). Gevers (1931, p. 5) stated that ‘no uncontestably striated stones have been found’; the same conclusion was reached by Smith (1965, p. 25) despite study of extensive outcrops of diamictite. This situation should be constrasted with that for glaciclastic deposits preserved in Spitsbergen where 15% of clasts are striated (see Section 4.1.10.2). Kröner (1981, p. 170) reported the presence of tectonically generated striations in the Chuos Group.

The tectonic setting of the Chuos Group is one of continental extension accompanying Rodinian breakup. Prave (1996) argued for a foreland basin depositional setting for the Chuos, but a rift-related setting for the turbidites and diamictites of the Chuos Group as first suggested by Martin et al. (1985) is now apparent (Hoffman et al., 1996; Duerr and Dingledey, 1997; Fig. 6). New age dates place important constraints on the timing of rifting. Igneous rocks related to rifting along the southern margin of the Congo craton yield dates of 756 ± 2 and 746 ± 2 Ma (Hoffman et al., 1996). These agree with the timing of rift-related magmatism in western North America (basal Windermere Group), Antarctica (Beardmore Group) and Australia (Sturtian). The dates establish a maximum age for the Chuos Group and allow a firm temporal association to be established with rifting during the initial phase of the breakup of Rodinia. The precise paleogeographic position of the Congo craton during deposition of the Chuos Group is not known, but is thought to have been located south of the eastern margin of Laurentia. As Rodinia broke up and the paleo-Pacific widened, Laurentia drifted into higher southern paleolatitudes.

Martin et al. (1985, p. 177) concluded that the sedimentology of the Chuos Formation can be readily explained in the absence of glacial activity although they recognised that small mountain or plateau glaciers could have formed locally on uplifted rift shoulders. Curiously, despite these findings, the Chuos Formation is still referred to as recording complete global refrigeration (Hoffman et al., 1998b, 1999; Corsetti and Kaufman, 1999; Halverson et al., 1999; Kennedy et al., 2001a; Condon et al., 2002) without any reference to the marine depositional origin and tectonic setting identified by previous workers.

4.1.4.2. Ghaub Formation. The much-reduced thickness of the Ghaub Formation is a major contrast with the underlying Chuos Group. Hoffman et al.’s (1998b) description of the Ghaub Formation is not helpful in understanding its depositional setting as it consists of a few brief sentences wherein description and genetic interpretation are mixed. The Ghaub apparently consists of ‘unstratified diamictons, debris flows and varvelike detrital couplets crowded with ice-rafted dropstones’. Reference is also made to the occurrence of large ‘horizontal plates’ of carbonate bedrock supposedly ‘detached from the directly underlying bedrock’ by ‘alternately grounded and floating sea ice’ (Hoffman and Schrag, 2000, p. 1342). This presumably is a reference to possible ‘glaciotectonic’ processes, but neither a mechanism nor supporting reference to the existence of any known modern, Pleistocene or Palaeozoic example is presented. Hoffman et al. (1999) omitted reference to glaciers and suggested instead that the Ghaub was deposited when the area was ‘entombed by grounded sea ice’. No mention is made by Hoffman et al. (1998b, 1999) of the origin of the massive diamictites, nor whether striated and shaped clasts are present nor how ‘varves’ could be present in a thick succession widely accepted as marine (Kennedy et al., 2001a). As we have emphasised above (Section 3.10), environmental interpretation of laminated facies is aided by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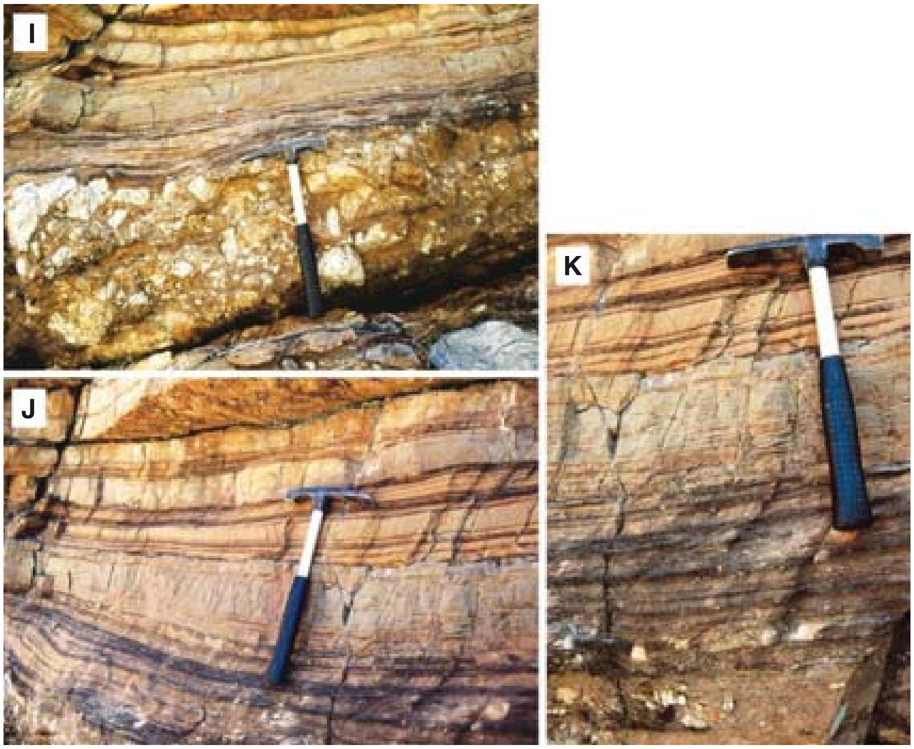


Fig. 11. Facies types; Ghaub Formation, Otavi Group, Namibia. No glacial influence can be identified and sedimentary structures indicate a normal hydrological cycle. (A, B, C) Massive diamictite (Dmm) composed of varicolored, locally derived, clastic carbonate; note figure (circled) for scale in (C). Facies were deposited as debris flows downslope of steep basin margins (Fig. 6). (D, E, F) Graded conglomerate beds (Gm) interbedded with diamictite. (G, H) Thin-bedded and laminated turbidite facies composed of graded, sand-sized clastic carbonate interbedded wihin diamictite. The same facies where they rest on uppermost diamictites are called 'cap carbonates' by Hoffman et al. (1998b). Hoffman (2002), Hoffman and Schrag (2002). (I, J, K) Maieberg 'cap carbonate' composed of thin-bedded turbidites resting on diamictite ('Pip's Rock'; Fig. 5). Note interbedding of 'cap carbonates' with diamictite below, in (K).

consideration of the local and basinal depositional setting (i.e., depositional 'context'). Using this approach, Stanton and Schermerhorn (1976, p. 57) and Schermerhorn (1977) identified a deep marine setting. Smith (1965) was also sceptical of the earlier varve interpetation of Gevers (1931) yet a terrestrial glaciolacustrine varve interpretation is still proposed by Hoffman et al. (1998b). These latter authors present no detailed descriptions of the sedimentology of the Ghaub Formation yet this is supposed to record catastrophic global refrigeration *unlike no other in Earth's history*. In this regard, we find it curious, that in their substantial review of the Snowball model, Hoffman and Schrag (2002) illustrate a glacially striated clast from North Africa deposits long accepted as glacial (Section 4.1.3), but fail to show *any* from Namibia where the role of glaciation is disputed (Martin et al., 1985) and where the demonstrated presence of such clasts is *absolutely fundamental to the credibility of the Snowball model*.

4.1.4.3. Sedimentary facies. Given major discrepancies between previous (Martin et al., 1985) and current (Hoffman and Schrag, 2002) interpretations of the sedimentary facies and origin of the Chuos and Ghaub formations, we examined well-exposed 'type Snowball' outcrops of the Otavi Group in central Namibia. The Ghaub Formation and the overlying cap carbonate (Maieberg) were examined at Fransfontein Gap and at Narachaamspos. Outcrops of the Chuos Formation and its respective capping carbonate (Rasthof) were examined at Lowenfontein and Omutirapo. In our opinion, both formations record a subaqueous slope depositional setting and consist entirely of a wide range of mass flow facies. Most of the debris is of local origin composed of reworked clastic carbonate derived from faulted underlying carbonate platform strata (Fig. 6). The Ghaub Formation is exclusively derived from underlying dolostones of the underlying Ombaatjie Formation, the Chous is lithologically more variable and, in addition to large rafts of the Ombombo Group, contains clasts of basement lithologies and vesicular basalt. Mass flows facies in both formations range from megabreccias, olistostromes, and debris flow diamictites produced by mixing of coarse and fine sediment and coarse-grained conglomeratic turbidites (Fig. 5). Fine-grained turbidites, composed of detrital silt- and sand-sized clastic carbonate, occur throughout and are no different from the immediately overlying so-called 'cap carbonates' previously inferred to have been deposited by direct postglacial precipitation from seawater (Hoffman et al., 1998b; Hoffman and Schrag, 2000; Figs. 5 and 11).

In referring to the Otavi Group, Hoffman (2002) states 'of the many Neoproterozoic successions bearing glacial deposits, none is richer in carbonate'. First, as others have done before us, we dispute the direct glacial origin of the Otavi Group (Section 4.1.4). We agree with Hoffman that such strata are very rich in *clastic* carbonate debris, but would point out that 'cap carbonates' *immediately* overlying diamictites in Namibia are detrital carbonates deposited by turbidity currents reworking clastic carbonate sediment (Fig. 11). The same so-called 'cap carbonate' facies, in fact, are present as interbeds throughout underlying mass flow diamictite facies. In general, the Namibian strata are dominated by huge volumes of reworked carbonate derived from faulted platforms and deposited in a deep marine slope setting (Fig. 6).

The lowermost parts of the Rasthof and Maieberg 'cap carbonates' are turbidite-dominated and display slumps and intraformational channeling testifying to an unstable slope and a continuing supply of detrital carbonate. The intriguing crystal fan deposits and other apparently primary carbonates described by Hoffman (2002) occur stratigraphically, several hundreds of metres above these facies (Hoffman and Schrag, 2002); use of the term 'cap carbonate' for such strata has already been questioned (Section 3.8.2.1).

In general, the carbonate slope depositional model of Coniglio and Dix (1992) describes the Ghaub and Chuos 'glacial' facies very well; we found no evidence that either of these formations are glacial or glacially influenced. We were unable to locate glacially striated or glacially shaped clasts or convincing ice-rafted dropstones. The prominent 'bedded dropstone horizon' repeatedly illustrated by Hoffman (2002), Hoffman and Schrag (2000, 2002) and Monastersky (1998) from the Ghaub Formation at Narachaampos supposedly records a 'final glacial collapse' of a Snowball Earth (Hoffman, 2002, p. 1). The same facies type occurs however, repeatedly below this horizon, interbedded with massive debris flow diamictites and conglomerates, but are not referred to by Hoffman in any of his publications despite their supposed global 'glacial' significance. In our opinion, these 'dropstone horizons' consists of crudely stratified diamictites deposited by successive debris flows carrying outsized 'lonestone' clasts (Figs. 5 and 7B, and Section 3.9).

The real significance of the Chuos and Ghaub formations is that they demonstrably show that Namibia was not extensively glaciated (Martin et al., 1985) and thus by extension, there was no global Neoproterozic glaciation. Dramatic climatic changes, unrivalled in the planet's history, have been inferred by Hoffman from these Namibian strata in the absence of any supporting detailed sedimentological information. It should also be noted that there is no agreement as to the age of the Chuos Group and Ghaub Formation; some (Hoffman et al., 1998b) interpret both as Sturtian, whereas Kennedy et al. (1998) placed the Ghaub into the Vendian.

4.1.5. Oman

The Neoproterozoic glacial record in Oman fully supports a tectonostratigraphic model developed in Part III of this paper, of regional ice cores nucleating on uplifted rift flanks. There, the sediment fill of several rift basins that are dated to $723+16/-10$ Ma record a normal hydrologic cycle in which glacially influenced diamictites, up to 100 m thick, accumulated by mass flows and rain-out in ice proximal margin environments. Up to five distinct cycles of glaciation were identified by Leather et al. (2002). Basinwide flooding surfaces and associated mudstones up to 200 m thick, are interpreted by these workers as the product of short-lived glacioeustatic sea-level rise. The thickness of these strata points instead to tectonic subsidence. Given the very active rift setting, suppression of eustatic sea-level changes may have been suppressed (see Section 5.1). Leather et al. (2002; p. 891) conclude, “On the basis of sedimentological and stratigraphic data, the Neoproterozoic glacials of Arabia were more like the familiar oscillatory glaciations of the Pleistocene than those required by the Snowball Earth hypothesis”.

4.1.6. South America

New paleoenvironmental data are forthcoming from the Neoproterozoic ‘glacial’ record of the Sao Francisco craton in Brazil confirming the importance of rift-related sedimentation during the breakup of Rodinia involving voluminous deposits of deep marine mass flows and turbidites (Martins-Neto et al., 2001). Regional ice covers formed on elevated rift shoulders. Because this area formerly lay contiguous with the Congo craton within Rodinia (Fig. 4), it confirms the rift-related tectonic setting and origin of the Chuos and Ghaub strata in Namibia (see below).

4.1.6.1. Brazil. Thick Neoproterozoic strata are preserved in the Aracuai fold belt of the Sao Francisco craton of eastern Brazil and accumulated in rift basins contiguous with ‘Sturtian’ strata (Chuos Group?) of the Damara Fold Belt. Two tectonically defined ‘megasequences’ (Macaubas–Salinas, 950–700 Ma and Bambui, ca. 800–650 Ma) occupy fault-bounded basins inset into the Sao Francisco craton and each contains a record of syn-rift to passive margin sedimentation. The oldest megasequence contains up to 8 km of mass flow-generated diamictites, conglomerates, sandstones and shales preserved in the main rift depocentre (Martins-Neto et al., 2001). Evidence of contemporaneous glaciation is restricted to grooved pavements at the base of relatively thin strata deposited on elevated portions of the craton. These strata contain conglomeratic facies interpreted as ‘ice-proximal alluvial fan’ deposits, but no striated clasts are present. Younger diamictites (Carrancas Formation) at the base of the overlying Bambui megasequence (formerly named the Jequitai Formation and interpreted as glacial by Trompette, 1994) show no evidence of a glacial origin (Martins-Neto et al., 2001, p. 364).

The great thickness of the Macaubas–Salinas megasequence is the product of the earliest ‘Sturtian’ phase of Rodinian breakup and rifting at about 750 Ma. Martins-Neto et al. (2001) invoke tectonically induced elevation as a trigger for local glaciation of rift shoulders possibly related to a mantle plume (Martins-Neto, 1998).

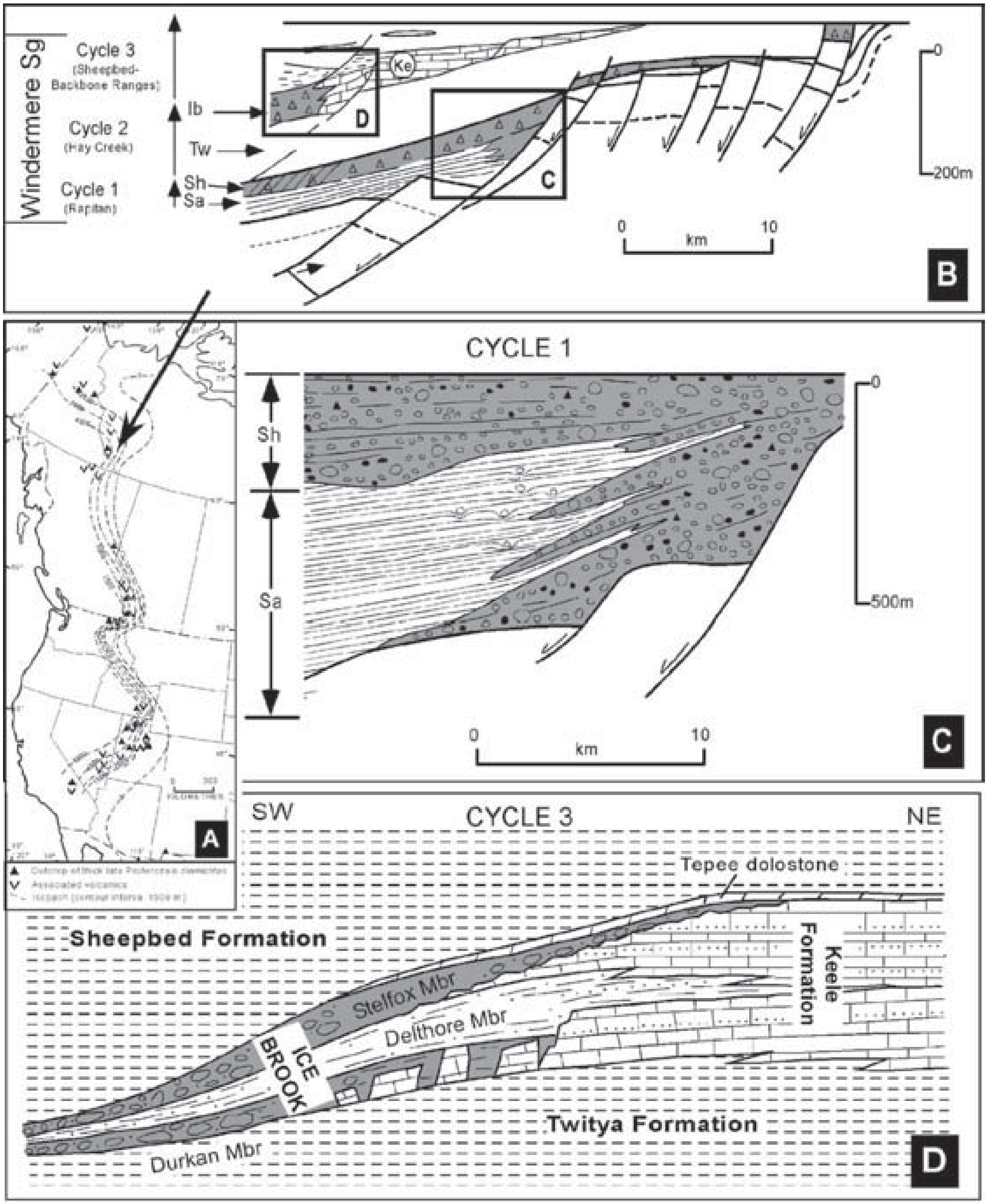
4.1.7. North America

In North America, Neoproterozoic glacigenic diamictites occur in rift-to-drift successions up to 6 km thick preserved along more than 30° of latitude of the paleo-Pacific margin of Laurentia. These extend from present day California to northwestern Canada (Fig. 12A). We do not propose to review each occurrence in detail as we note a similar overall architecture from one basin to another, indicating a shared paleo-tectonic setting (Ross et al., 1995). Glaciogenic deposits occur at the base of very thick passive margin successions that together form well-defined, tectonically controlled megasequences (e.g., Kingston Peak diamictites, Abolins et al., 2000; Fedo and Cooper, 2001; Fig. 11B). Data identify deposition in rapidly subsiding marine rift basins along the embryonic paleo-Pacific margin of Laurentia and a strong control on sedimentation by active tectonics.

4.1.7.1. Windermere Supergroup of Canada. The 5–7-km-thick Windermere Supergroup contains several well-defined unconformity-bounded successions termed ‘grand cycles’ by Narbonne et al. (1994; Narbonne and Aitken, 1995). Each cycle is dominated by deepwater slope turbidite facies and generally displays a coarsening/shallowing upward character from siliclastics to carbonates (Aitken, 1991a,b; Narbonne and Aitken, 1995; Fig. 12). Lowermost deepwater turbidites contain large carbonate slide blocks up to 30 m in length, derived from the downslope collapse of a faulted carbonate platform recording the start of a new episode of faulting and basin subsidence. The overall basin architecture is comparable to that of Namibia (compare Figs. 6 and 12).

The oldest ‘grand cycle’ in the Windermere Supergroup is composed of nonmarine to shallow marine siliclastics and carbonates capped by the Rapitan Group consisting of the glacially influenced marine Sayunei and Shezal formations (Eisbacher, 1981; Fig.

12C). There is substantial agreement that glacial deposits record sedimentation in an active rift setting (Narbonne and Aitken, 1995; Ross et al., 1995) that was likely contiguous with the similarly thick Sturtian succession of the Adelaide Rift Complex of southern Australia. Taken together, the Rapitan and



Sturtian record opening of a paleo-Pacific Ocean along the western margin of Laurentia (Young, 1992a, 1995; Fig. 4A). The Rapitan is overlain by 'grand cycles' of the Twitya-Keele, Sheepbed-Gametrail and Blueflower-Risky formations (Fig. 12B,D). The Sheepbed-Gametrail cycle contains glacially influenced facies of the Ice Brook Formation that are regarded as correlative to the Marinoan of Australia (Aitken, 1991a,b).

A brief review of the tectonic setting and stratigraphy of the Windermere Supergroup was presented by Eyles (1993, p. 96–99) who argued that each 'cycle' is a tectonostratigraphic succession recording successive episodes of rifting and subsidence along the paleo-Pacific continental margin of western Laurentia. Narbonne and Aitken (1995) report an age date of younger than 755 Ma for the base of the Windermere Supergroup. The following sections place the Rapitan and Ice Brook glacials into their tectonic 'context'.

4.1.7.2. Rapitan Group. The deep marine mass flow origin of diamictites of the Rapitan Group is demonstrated by their thickness, geometry and associated facies. Diamictites have maximum thicknesses of several hundreds of metres and have a wedgelike architecture thinning basinward from faults (Fig. 12C). Diamictites are interbedded with huge carbonate olistrostromes, contain clasts of entirely local derivation only, and are interbedded with basinal turbidites. Convincing evidence for a glaciclastic source for the Rapitan diamictites, is described by Young (1976) and Eisbacher (1985). The overall depositional setting appears to be a glacially influenced shelf and slope with a regional architecture composed of shelf 'topsets' and slope 'foresets' abutting fault scarps. These are perhaps analogous to those of modern high-latitude glaciated shelves, such as Antarctica, that experience rapid progradation during glaciation (Anderson, 1999; Eyles et al., 2001a,b).

Ross et al. (1995) and McMechan (2000) discuss correlative diamictite and turbidite deposits of the Purcell and Cariboo Mountains such as the 2500-m-thick Toby Formation and Mount Vreeland Formation. Ross et al. (1995) concluded that the Windermere Supergroup was deposited across a submarine slope/fan comparable in size to the modern day Astoria or Monterey fans. He reviewed evidence of lateral facies variability in response to active syndepositional faulting and showed that diamictites are laterally equivalent to thick turbidite successions (e.g., Kaza and Horsethief Creek formations of the Cariboo-Purcell Mountains). It is significant that ice rafted debris is absent from these correlative deep marine deposits which indicates the limited reach of floating ice during glaciation. The picture emerges of a restricted regional ice cover that only locally reached sea level, and the fluvial transport of enormous volumes of coarse and fine sediment to steep rift basin margins. These are not characteristics that would be expected of a Snowball Earth.

4.1.7.3. Ice Brook Formation. The 'glacial' Ice Brook Formation defines the top of the Twitya-Keele cycle according to Aitken (1991a; Fig. 12D) and is correlated with the Varanger and Marinoan glacial interval. Evidence for a glaciclastic sediment input during deposition is very sparse however, and as Aitken (1991a) frankly admitted 'fail to fulfill expectations under a glacial model'. He identified ice-rafted 'dropstones' and 'till pellets', but the origin of these is very unclear and alternative nonglacial explanations are viable (see Section 3.9; Fig. 7A). Nonetheless, he collected two glacially striated clasts from 300-m-thick outcrops which contrasts with the much greater frequency of striated clasts (between 14% and 30%)

Fig. 12. (A) Neoproterozoic diamictites of the western Cordillera of North America and thickness of rift-related strata deposited along rifted Palaeo-Pacific margin of Laurentia. (B) Restored rifted margin of Late Proterozoic Windermere Supergroup basin showing the three stratigraphic 'cycles' of Eisbacher (1985) within glacially influenced strata of Cycle 1 (Sayunei, Sa; Shezal, Sh) and Cycle 3 (Ice Brook Formation, Ib). Tw: Twitya Formation; Ke: Keele Formation (after Eisbacher, 1985; Aitken, 1991a,b). Each cycle is identified as as the response to renewed rifting, shedding of carbonate debris and subsidence along a palaeo-Pacific margin of Laurentia. Regional glaciation occurs in response to broad uplift of the continental margin inboard of the developing rift. (C) Down basin cross-section through infill of diamictites and turbidites of the Windermere Supergroup. Strata record intermittent uplift of source area glaciation and progradation of debris flows into turbidite basin. Fig. 13 shows correlative strata deposited along the then opposing Australian margin of the palaeo-Pacific ocean and related to rifting of Rodinia after ca. 750 Ma. Compare with Fig. 6. (D) Ice Brook Formation showing very clear relationship between diamictites, olistostromes and rifted carbonate margin of Laurentia forming a distinct tectonostratigraphic succession (after Aitken, 1991a).

present in tills and tillites deposited directly below ice sheets (e.g., Visser, 1987; Hall, 1983; Visser and Loock, 1988).

A regional cross-section through the Ice Brook Formation clearly suggests a deepwater (below wave base) 'mass flow-dominated' slope, adjacent to active faults (Fig. 12D). It is likely given the rifted topography of the time and the marine setting, that any ice cover was likely restricted to adjacent upland areas on rift flanks. Narbonne et al. (1994) placed the Ice Brook Formation at the top of their Twitya-Keele cycle, but mass flow deposits could well be syn-rift in origin marking the *base* of the overlying Sheepbed-Gametrail cycle. The three component members of the Ice Brook Formation (Durkan, Delthore and Stelfox) record distinct episodes of downslope mass flow accompanying repeated phases of source area uplift. Minor diamictites, olistostromes and 'lonestones of uncertain origin' (Narbonne and Aitken, 1995, p. 111) are common; striated clasts occur in the Stelfox. In turn, these strata are blanketed by deepwater shales of the Sheepbed Formation that record strong postrift subsidence of the basin. The strong intimacy of glaciation and rifting is well demonstrated. In their detailed study of the Ice Brook cap carbonate. James et al. (2001) indicated deposition in seawaters only weakly influenced by glaciation and could not recognise evidence of the severe and abrupt postglacial changes in temperature and PCO_2 required by the Snowball Earth model.

4.1.7.4. Western Cordillera of southern Canada and the United States. Recent detailed work in Canada by Ross et al. (1995) and McMechan (2000) and by Link et al. (1993) on broadly correlative successions elsewhere in the western United States Cordillera, such as in California, Utah and Idaho, provides a clear picture of glacially influenced marine sedimentation in rift settings with abundant sediment supply and a normal hydrological cycle. Link et al. (1993) emphasised the role of rift shoulder uplift in initiating and controlling the location of ice centres and in dictating the sedimentary record, dominated by deepwater slope facies.

Very recently some of these deposits have been reinterpreted in classical 'Snowball' terms despite much uncertainty as to age dating and whether truly 'glacial' strata (tillites) are present; much of this recent work can be said to be 'model driven' and the influence of tectonics on deposition and the evolution of stratigraphic successions is scarcely alluded to.

In the Death Valley region of southeastern California, the Kingston Peak Formation contains two diamictites (Wildrose and Surprise diamictites), up to 400 m thick, and deepwater carbonates (Sourdough Limestone and Noonday Dolomite). Initially, the Kingston Peak Formation was thought to be a record of repeated glacial events within a Sturtian glaciation, but this was tempered by recognition of abrupt lateral changes in thickness and facies and the presence of large allochthonous blocks (Link et al., 1993), indicating a strong tectonic control on basin evolution, water depths and filling history. Despite this dynamic depositional setting, Prave (1999) reinterpreted the succession using 'bed-for-bed' correlations with other synrift strata elsewhere in the Cordillera. He simply identified two 'glacial' diamictites as an individual record of glaciation, one Sturtian and the other Marinoan. A glacial origin was inferred from the presence of isolated lonestones and horizons of lonestones, interpreted as dropstones, and very rare striated clasts. The diamictites contain large carbonate olistostromes and thick (tens of metres) interbeds of carbonate strongly, suggesting reworking and recycling of carbonate from underlying units. In their detailed review, Link et al. (1993) clearly identified a rift-related origin and stratigraphic and sedimentologic variability arising from ongoing syndepositional tectonics in a graben basin. Given this intrabasinal control by tectonics on sedimentation, identification of individual glaciations and associated eustatic changes using traditional climatostratigraphic 'bed for bed' criteria are unconvincing.

The Sourdough and Noonday 'cap carbonates' yield negative $\delta^{13}C$ values consistent with the idealized Snowball signature (Hoffman and Schrag, 1999). In addition, however, similar isotopic values have been obtained from carbonates *within* the Kingston Peak Formation that are stratigraphically positioned well above and below the 'Snowball' units mentioned (Kennedy et al., 1998; Corsetti and Kaufman, 1999). In this case, additional 'glacial' diamictite units are absent necessitating the introduction of the term 'cap-like carbonates' into the Snowball model (Corsetti and Kaufman, 1999). As a consequence, some workers have proposed that it is possible to identify *global catastrophic glaciation* based solely on negative 'Snowball-like' $\delta^{13}C$ excursions and 'caplike' facies present in supposedly postglacial carbonates (Abolins et al., 2000; Corsetti and Kaufman, 1999; Kennedy et al., 1998). With this in mind, incised horizons and karst surfaces in the Noonday Dolomite and Johnnie Formation have been interpreted as a record of glacioeustatic lowstand (Abolins et al., 1999). Glacioeustacy was invoked because these features postdate a positive $\delta^{13}C$ excursion and are overlain by a carbonate with 'caplike' facies and negative $\delta^{13}C$ values. Significantly, clasts within incision fills are derived from as much as 1.5 km down section, suggesting strong tectonic uplift during this period (Summa et al., 1993; Link et al., 1993) and a dominantly tectonic, not climatic, control on water depths.

4.1.7.5. Avalonian–Cadomian orogenic belt (eastern North America, France). The circum-Atlantic Avalonian–Cadomian orogenic belt contains several diamictite–turbidite successions now widely scattered around the margins of the North Atlantic. They are all likely deep marine in origin, deposited on submarine fans. Some successions, such as the Gaskiers Formation of Newfoundland, show a weak glacial influence consisting of rare striated clasts (Eyles and Eyles, 1989). The extent of glacial influence on others, such as the famous 'Squantum Tillite' of the Boston Bay Group of Massachusetts (Dott, 1961; Socci and Smith, 1987; see Section 3.1.3.1) and diamictites of the Brioverian Supergroup of Normandy (Winterer, 1963; Eyles, 1990) is questionable. All of these successions attracted the attention of glacial geologists simply because of the presence of thick diamictites ('tillites'), laminated argillites ('varvites') and possible dropstones (e.g., Sayles, 1914, 1919; Dore et al., 1985 and refs therein; Section 3.1.3.1), but it has long been recognised that evidence was weak (Dott, 1961). Tectonic settings for those of the Cadomian Belt are volcanic arcs (Gaskiers, Brioverian, Boston) characterised by large volumes of volcaniclastic sediment and high sedimentation rates, tectonic instability and deep-water, mass flow-dominated slope environments recorded by very thick successions of thick-bedded diamictites (>50 m thick) and turbidites. Available ages indicate a late Neoproterozoic age younger than 595 Ma and thus 'post-Marinoan' (Thompson and Bowring, 2000). The rift-related, but poorly dated (750–570 Ma; Rankin, 1993), Neoproteropic Konnarock Formation of Virginia (formerly Upper Mount Rogers Formation) also shows a possible, but weak glacial influence (Miller, 1994). Taken together, these strata support the notion of regional, tectonically controlled ice centres.

4.1.8. Australia

4.1.8.1. Sturtian. The Sturtian is named after classic outcrops of diamictite exposed within the Sturt Gorge near Adelaide, South Australia and deposited within the Adelaide Rift Complex (Mawson, 1949; Figs. 2G,H and 13). The Adelaide Rift Complex (ARC) is one of several large Neoproterozoic basins (Officer, Ngalia, Amadeus) that trend northwest/southeast across the country west of the Tasman Line. These basins are separated by upstanding basement blocks and were interpreted as failed rift arms by Veevers and McElhinny (1976) and Lindsay et al. (1987). Mafic dyke swarms across this large area have a uniform geochemistry, suggesting the influence of a mantle plume (Zhao et al., 1994).

Recent deep drilling of Sturtian strata in the Officer Basin (at Vines I and Empress I) by the Geological Survey of Western Australia show the presence of very thick (up to 2 km) successions of turbidites and mass flow diamictites recording very rapid subsidence and sediment accommodation (Grey et al., 1999; Eyles et al., 2003; see also Lindsay, 1989; Lindsay and Brasier, 2002 for the Amadeus Basin). Nelson (2001) identified surrounding cratons, such as the Musgrave Complex or Albany–Fraser Orogen, as likely source areas on the basis of detrital zircons isolated from diamictites. In the Adelaide area where they are best known, diamictites of the Yadnamutana Subgroup are characterised by their great thickness and intimate association with turbidites containing ice-rafted dropstones (Wilyerpa Formation). These are preserved in graben subbasins within an elongate northwest-trending rift. In turn, they are draped by an extensive blanket of turbidites as much as 2.4 km thick (Tapley Hill Formation) regarded as recording postglacial glacioeustatic transgression (Drexel et al., 1993; Li and Powell, 2001; Preiss, 1999; Fig. 13).

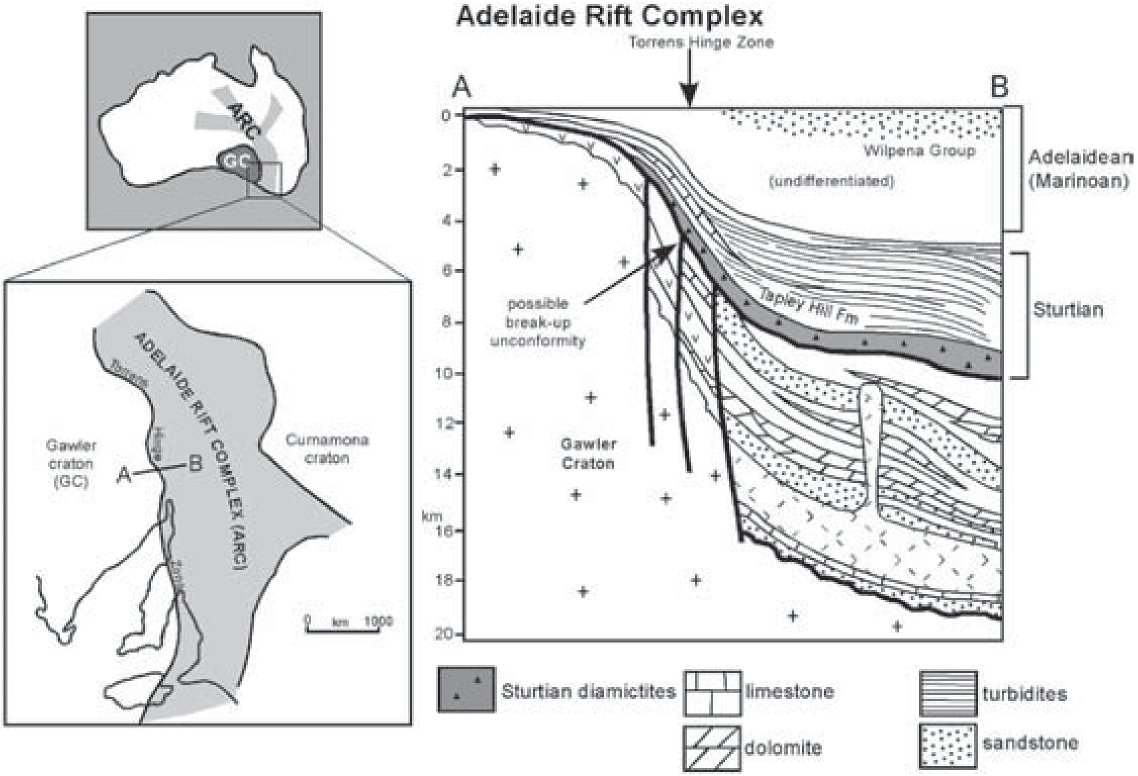


Fig. 13. Australia. Sturtian diamictites and associated turbidites of the Adelaide Rift Complex. Note similarity with Figs. 6 and 12.

Detailed facies descriptions of Sturtian diamictites in the Mount Painter area of the northern Flinders Ranges are given by Young and Gostin (1989, 1991) and Young (1992b). They demonstrate a deepwater glacially influenced submarine slope/fan setting. The thick and massive Sturtian diamictite facies of South Australia previously interpreted as subglacial by Link and Gostin (1981, p. 39) and other workers (e.g., Fig. 2C,E) have been shown to be sediment gravity flows (Young and Gostin, 1988, 1989, 1990, 1991). The term ‘tillite’ is still employed in formal stratigraphic terminology (e.g., Pualco Tillite), but it is widely agreed that diamictites are marine mass flows deposited in rapidly subsiding graben subbasins between uplifted glaciated basement blocks of the Gawler and Curnamona cratons (Fig. 13). Giant granite olistostromes, up to 800 m in length, occur within thick diamictites lying adjacent to the faulted basin margins (Drexel et al., 1993; Preiss, 1999). The thickness of massive diamictites is impressive; that of the Bolla Bollana ‘Tillite’ reaches 2500 m in theYudnamutana Trough of the northern Flinders Ranges and the Pualco ‘Tillite’ is more than 3300 m thick in the Barrat Trough of the central Flinders Ranges. These record the delivery of large volumes of sediment and an active hydrological cycle.

Elsewhere, thick successions of turbidites and mass flow diamictites, possibly correlative with those of the Adelaide Rift Complex, occur within a broad belt across central Australia consisting of distinct basins (e.g., Officer), but grouped under the term ‘Centralian Superbasin’.

The Sturtian of Australia marks the base of ‘Supersequence 3’ of Walter et al. (1995) in the Centralian Superbasin and Adelaide Rift Complex. This event records the initial rifting of that part of Rodinia after 750 Ma and rapid subsidence of its formerly contiguous margins (Li and Powell, 2001). Overlying turbidites mark the rift-drift transition and the formation of a passive margin along the paleo-Pacific Ocean. The same overall tectonostratigraphic evolution is apparent in China (Section 4.1.9), southern Africa (Section 4.1.4), Brazil (Section 4.1.6), western North America (Section 4.1.7) and China (Section 4.1.9). Using paleomagnetic data and ion microprobe U–Pb dating of dyke swarms across the Pilbara craton of Western Australia, Wingate and Giddings (2000) argued that the Sturtian of Australia is not strictly coeval with strata of the Windermere Supergroup of northwest Canada. Such diachroneity is to be fully expected under a model of diachronous rifting and glaciation across Rodinia (Section 5.1.4).

Other Sturtian Neoproterozoic strata in Australia, spanning putative Snowball glaciations, occur in Tasmania. Significantly, these show *no* evidence of any glacial imprint (e.g., Togari Group, Griffin and Preiss, 1976; Calver, 1998). This belies extensive glaciation of the Australian landmass at this time.

Related Sturtian glacial deposits occur in Mongolia. Glacial diamictites, showing 'oriented and weakly striated clasts' occur in the Maikhan Uul Member at the base of the Tsagaan Oloom Formation in the Zavkhan Basin of western Mongolia (Brasier et al., 1996a,b; Lindsay et al., 1996). A rift setting was inferred by Lindsay et al. (1996) and closely correlated to Sturtian glaciation of Australia and northwest Canada after 750 Ma. Evans et al (1996) demonstrate that paleomagnetic data have been reset in the Silurian–Devonian.

4.1.8.2. Marinoan. True glacial tillite and striated pavements occur in the Kimberley area of northwestern Australia (e.g., Walsh, Landrigan, Moonlight Valley tillites) and are regarded as Marinoan in age (Grey and Corkeron, 1998; Corkeron and George, 2001; K. Grey, personal communication, 2002). A possible younger late Marinoan glaciation has also been identified (Egan Formation; Grey and Corkeron, 1998) based on the presence of the stromatolite *Tungussia Julia* which elsewhere, occurs in the Julie Formation of Amadeus Basin and Wonoka Formation of the Adelaide Rift Complex. More work is needed on the tectonic setting of the Kimberley area, but its location as an elevated block of Archean crust adjacent to the large Neoproterozoic basins of central Australia may suggest local uplift-driven ice covers.

As we have already stated (Section 3.7.2), considerable uncertainty surrounds the sedimentology and depositional setting of Marinoan 'type' strata exposed in southern Australia. Evidence of a Marinoan glaciation hinges on outcrops first described by Mawson (1949) from the Stuart Shelf in the vicinity of Elatina Hut of the Central Flinders Ranges. This section is not, apparently, fully representative and Lemon and Gostin (1990) provided detailed facies descriptions of six additional outcrops of the Elatina Formation, and attempted regional correlations. Diamictites reported by Lemon and Gostin (1990) are bouldery, poorly sorted conglomerates. They rest unconformably on the Trezona Formation with the contact marked by boulder lag deposits at the base of channels that are filled with coarse-grained cross-bedded sandstone. Sandstones are extensively slumped. Exotic striated clasts were ascribed to glacial transport from the Gawler craton 200 km to the west, but Preiss (1990) suggested that clasts were derived locally from the nearby Oraparinna Diapir. Syndepositional tectonism was a continuous occurrence throughout deposition of the Elatina in response to upward movement of diapirs within the basin fill. Slumped sandstones may correspondingly be 'seismites'.

Outcrop descriptions testify to the importance of fluvial and shallow marine sedimentation around islands formed by the upward growth of diapirs. These islands, according to Lemon and Gostin (1990, p. 161), were able to support 'local ice caps', but no detailed argument is provided. A possible alternative explanation is that no glaciers were present, but that erosion of the subaerial portions of diapirs furnished a supply of exotic and *tectonically striated* clasts to surface fluvial and shallow marine environments. We note that intrusion of diapirs, composed of brecciated country rock, is responsible for bringing deep basement lithologies to the surface throughout the Adelaide Rift Complex (Webb, 1960; Preiss, 1990, p. 11). Lemon and Gostin (1990) themselves describe outcrops very close to the Enorama Diapir and state that 'a diamictite at the top of the formation which again shows local derivation from an exposed nearby diapir' (p. 157) thus, in effect denying a role for glaciers. Preiss (1990) considered that Marinoan glaciation was restricted to northern parts of Australia with cold, periglacial conditions across the Stuart Shelf. In southern Australia, the Elatina Formation is overlain by dolomites of the Nucaleena Formation that are of detrital clastic origin; much of the underlying Elatina contains dolomite cement and concretions derived from the diagenesis of clastic carbonate dragged up by diapirism from underlying limestones (most likely the Curdimurka Subgroup; Lemon, 1985; Preiss, 1987, 1990).

Evidence of a regional cold climate during Marinoan time is in the form of wedge-shaped sedimentary dikes in strata correlative with the Elatina (Whyalla Sandstone, Williams, 1986). Wedge-shaped structures, interpreted as 'ice wedge casts' produced by deep ground freezing at very low mean annual temperatures, occur in the Cattle Grid Breccia of the Mount Gunson area (Williams and Tonkin, 1985; Williams, 1986). There is uncertainty regarding the age of such strata and their precise stratigraphic relationship with the Elatina Formation (see Fig. 2 in Williams and Tonkin, 1985). Wedge-shaped 'liquefaction pillars', convolutions and sand dikes are generated in areas subject to strong seismicity, but a periglacial origin for the structures in the Cattle Grid Breccia is convincing.

4.1.9. China

The South China Block lies close to Australia in most Rodinian reconstructions (e.g., Fig. 4A) and, not surprisingly, there are many stratigraphic and sedimentologic similarities between the Neoproterozoic glacial records of the two areas (Eisbacher, 1985; Eyles, 1993). The oldest intervals in China (Chang'an and Nantuo formations) are poorly dated, but possibly Sturtian in age. Evans (2000); (Evans et al., 2000) cites an age of 748 ± 12 Ma for the Liantuo Formation which lies stratigraphically between these two. They approach 4 km in thickness and show diamictites interbedded with turbidites and substantial thicknesses of submarine lavas and volcanogenic debris (see Lu and Zhenjia, 1991). A glacially influenced marine origin is apparent and the overall stratigraphic succession suggests deposition in elongate aulacogen basins with a strong volcanic and glacial influence (Wang et al., 1981; Eyles, 1993). Li et al. (1999) argued that a mantle plume below South China initiated the breakup of Rodinia.

The youngest Neoproterozoic (Marinoan?) glaciogenic strata in China (Zhengmuguan/Luoquan Formation) are restricted to the North China Block that then lay east of Siberia. Data from the Tarim region, reported by Zheng et al. (1994), identifies a glacially influenced deep marine rift basin succession of lowermost massive diamictites with carbonate olistostromes overlain by stratified and graded diamictite facies and thick turbidites similar to that inferred for the North China Block strata (Guan et al., 1986; Brookfield, 1994).

A consistent picture begins to emerge of Sturtian glacially influenced marine sedimentation across much of central Rodinia involving glaciation on the uplifted margins of a large triple junction between Australia, the South China Block, Siberia and the western margin of Laurentia (Fig. 4A).

4.1.10. Circum North Atlantic region of Northwest Europe

The late Neoproterozoic was a time of protracted lithospheric extension in northwest Europe (Vidal and Moczydlowska, 1995). Rifting during the Riphean and Vendian culminated in the opening of the early Iapetus Ocean along the eastern margin of Laurentia just before 600 Ma (Fig. 4B). Broadly correlative Riphean rift-related clastic wedges occur around the North Atlantic in Greenland (Eleonore Bay Supergroup), Svalbard (Hecla Hoek) and Scotland (the Torridonian Supergroup, Moine Supergroup, Grampian and Appin Groups). These thick wedges are dominated by compositionally immature sandstones and conglomerates (Soper and England, 1995; Glover et al., 1995; Smith et al., 1999; Higgins et al., 2001). All these strata are overlain by Vendian (Varanger) glaciogenic deposits consisting of glacially influenced marine facies deposited during the separation of Baltica from eastern Laurentia (Nystuen, 1985; Eyles, 1993). A mid-latitude site of deposition is indicated (Torsvik et al., 1996). Age control for the Varanger glaciation is derived from a Rb/Sr age for the Nyborg Formation of 650 Ma. In general, the glaciogenic strata are of synrift origin and are overlain by deepwater shales recording maximum basin subsidence. Ultimately, shales pass up into shallow marine facies.

4.1.10.1. North and East Greenland. Extensive and well-exposed outcrops of ice-contact glaciomarine deposits occur in the fiord region of East Greenland (Tillite Group of Hambrey and Spencer, 1987) and have been reported as by Moncrieff and Hambrey

(1988) and Moncrieff (1990). These workers interpreted a variety of diamictites and matrix supported conglomerates as 'basal tillites' containing intraformational rafts of 'subaqueous outwash' and other meltwater deposits, 'waterlain tillite', 'transitional residual', 'proximal–transitional', 'compound glaciomarine', 'proximal–transitional' and 'proximal compound' diamictites using the classification of Anderson (1983). Glacial sedimentologists no longer imply such terminology because there is now a much better understanding of depositional processes on glacially influenced marine settings (e.g., Anderson, 1999).

Evidence of a glacial influence in Greenland is convincing and reexamination of lithologic logs of Moncrieff and Hambrey (1988) suggest that diamictite facies are varieties of debris flows most likely deposited on a deep marine slope below wave base. Diamictite beds have a variable matrix content, are sharp-based, contain numerous rafts of sediment, and are intimately interbedded with muddy turbidites that considered together comprise a classic 'mass flow-dominated' succession. No facies transitions recording emergence or transgression are present and the context of massive and crudely graded sandstones suggests Bouma A divisions of turbidites. Herrington and Fairchild (1989) related deposition of the Tillite Group to basin extension; the Lower Tillite rests abruptly on an underlying carbonate platform and contains large volumes of reworked clastic dolomite as is typical of many other Neoproterozoic diamictites. In northern Greenland, Sonderholm and Jepsen (1991) describe syntectonic glacial facies preserved in an aulacogen related to Neoproterozoic rifting of the Franklinian Basin (Surlyk, 1991). Collinson et al. (1989) describe terrestrial (rift?) valley fills containing reworked glacial facies.

4.1.10.2. Svalbard. In the northeastern part of Svalbard (northeast Spitsbergen and Nordaustlandet), Vendian diamictites of the Polarisbreen Group (Wilsonbreen and Elbobreen formations; Hambrey, 1982) are interbedded with shales. Up to 15% of clasts are striated and a glacially influenced marine setting fringed by wet-based glaciers is indicated. Hambrey (1989) stressed the sedimentological similarities with the Tillite Group of East Greenland and inferred deposition in the same basin (Fairchild and Hambrey, 1995; Harland, 1997).

4.1.10.3. Scandinavia, Scotland, East European platform and Siberia. The Neoproterozoic of this wide region has most recently been reviewed by Vidal and Moczydlowska (1995). The stratigraphic record is dominated by rift basin fills, but evidence of glaciation is not everywhere present in coeval strata, most likely indicating a restricted distribution of glaciers perhaps on elevated rift shoulders and plateaux. Emplacement of dolerite swarms and episodic basaltic magmatism record several phases of rift basin formation and the preservation of strata in aulacogens after 750 Ma, but especially between 650 and 610 Ma, accompanying the Varanger glaciation. Glacially influenced marine sedimentation is inextricably linked to what was described as a 'resurgence of synrift sedimentation' (Higgins et al., 2001) that took place in mid-to-high paleolatitudes along the paleo-Atlantic (Iapetus Ocean) margin of Laurentia (Fig. 4B). It can be noted that glaciogenic facies of northern Norway (Smalfjord Formation) have nonglacial equivalents in the Hedmark Basin of southern Norway (Biri Formation; Vidal and Moczydlowska, 1995). The layer contains thick, wedge shaped conglomerate bodies of mass flow origin that interfinger with turbidites and record active rifting; contemporaneous rift-related, but nonglacial deposits also occur in the Vattern Basin of Sweden (Vidal and Moczydlowska, 1995, p. 203). In keeping with then available depositional models, past work on the glacials of northern Norway interpreted massive diamictites as tillites deposited by grounded glaciers (e.g., Edwards, 1975, 1984); new work stresses the importance of resedimentation of glaciclastic sediment in a marine basin and the absence of any facies directly deposited by glaciers.

Of particular note is the occurrence of large folded carbonate olistoliths within the Port Askaig Tillite deposit in the Argyll Group of Scotland (e.g., Great Breccia, Spencer, 1971; Eyles and Clark, 1985; Arnaud and Eyles, 2002, Fig. 5D,E) and Finnmark within glacially influenced marine diamictites. These record major submarine landslides during rifting. Scottish diamictites are associated with thick tidally deposited sandstones and contain granitoid boulders possibly of South American origin (Evans et al., 1998). The overall similarity of carbonate-rich mass flow facies of the Great Breccia and those of the Namibian Neoproterozoic (Chuos Formation) is impressive (Fig. 5). These, and other such deposits, testify to widespread faulting of carbonate platforms and the shedding of carbonate-rich debris to newly rifted Neoproterozoic basins (see Section 5.1.3.1 and Fig. 14).

4.2. Statement of findings of Part II

(1) Neoproterozoic tillites, deposited directly by glacier ice on continental land surfaces, and resting on striated unconformities, are rare in the stratigraphic record. Possibly the best preserved and most extensive terrestrial record of Neoproterozoic glaciation occurs within the Taoudeni Basin on the West African craton of northwest Africa. Given the cratonic setting, the possibilities for subsequent erosion and reworking were reduced. This could provide a clue as to the preservation of Neoproterozoic tillites elsewhere in the geologic record and helps explain the occurrence of Surtian and Marinoan Neoproterozoic tillites on the Kimberley craton of Australia.

(2) Neoproterozoic diamictites are not a unique sedimentary *motif* of a Snowball Earth. Most were generated as mass flows (debrites and associated slope facies) in tectonically active marine basins. They are intimately associated with genetically related turbidites having accumulated on submarine fans and slopes. Thick debris flow diamictites were most likely produced by mixing of different textural populations during downslope slumping and flow; the term ‘mixtite’ is appropriate. These deposits indicate a normal fully functioning hydrologic cycle. Diamictites and other poorly sorted sediment gravity flow facies are a very common and conspicuous Neoproterozoic facies type because of faulting and landsliding associated with widespread Rodinian ‘megarifting’; the same facies appear to have been produced regardless of paleolatitude.

(3) Some Neoproterozoic diamictites contain a well-defined component of glaciclastic sediment

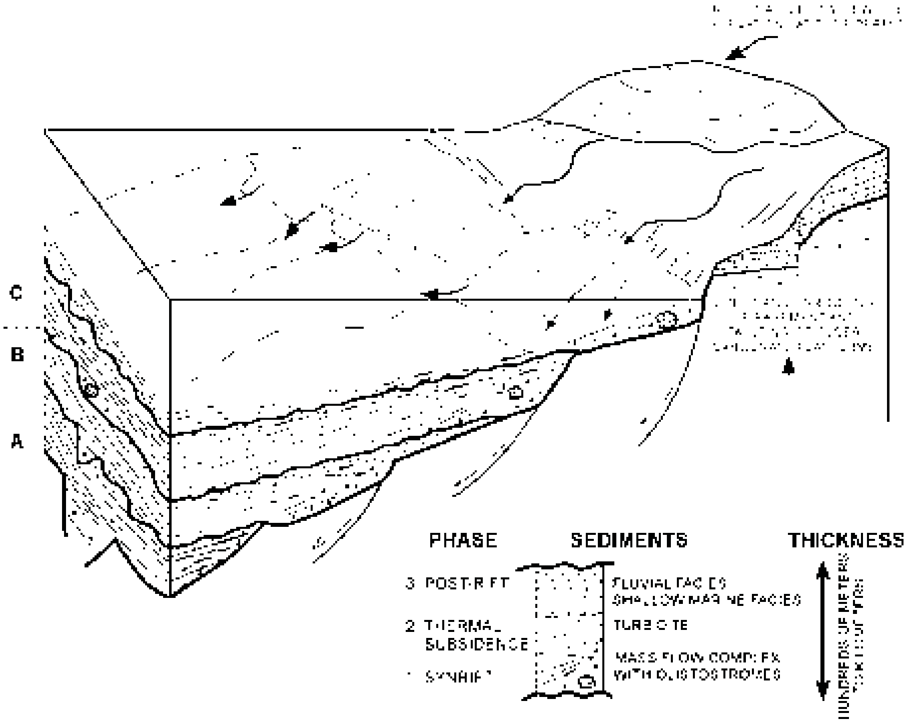


Fig. 14. Formation of ‘tectonostratigraphic’ successions along a rifted basin margin. Each cycle starts with basin subsidence and source area uplift followed by an influx of subaqueous mass flows (synrift diamictites). Thick prograding turbidite successions record thermal subsidence. The tectonic cycle is completed by shallow marine and fluvial facies of the postrift phase of basin development creating a tripartite tectonostratigraphic succession (modified from Eyles, 1993). Compare with Figs. 6, 12 and 13).

(dropstones, till pellets, striated clasts) recording the release of sediment from land-based ice sheets or glaciers to the marine environment. The term 'glacially influenced' is appropriate in these cases. The primary record of terrestrial glaciation (e.g., tillites, etc.) on adjacent land surfaces exposed to uplift and erosion, has been lost.

(4) Sturtian and Marinoan glacially influenced strata were deposited predominantly in rift basins and newly formed passive margins of the paleo-Pacific and Iapetus oceans. There are striking similarities between deep marine successions now preserved in China, Australia and western North America. Glaciation was likely regional in extent and triggered by tectonic uplift of passive mountains and rift shoulders. The intimate relationship between Neoproterozoic glaciation and tectonic activity is demonstrated because glacially influenced marine strata, dominated by mass flow diamictites and turbidites, comprise syn-rift strata within thick 'tectonostratigraphic successions'. Simple 'bed-for-bed climatostratigraphic' interpretations of these successions and recognition of glacioeustatic fluctuations in sea level is complicated by a dominant, tectonic control on facies, facies variability, relative water depths and basin filling histories.

In Part III of this paper, we explore the relationship between tectonics and glaciation in more detail and attempt to formulate a simple tectonostratigraphic model for the Neoproterozoic.

5. Part III: a tectonostratigraphic model for Neoproterozoic glaciations and deposits

5.1. Glaciation and tectonics

The wealth of the Pleistocene climate record allows detailed reconstruction and modelling of climate change on extremely short time scales (e.g., Alley, 2000). The roles played by Milankovitch astronomical variables, changes in atmospheric chemistry and ocean circulation, by icebergs, meltwaters and ice sheet substrates are now identified (Bond et al., 1992; Broecker, 1994; Hostetler et al., 1999; McManus et al., 1999; Licciardi et al., 1999). This detail tends to obscure the larger picture that the Pleistocene glacial epoch had longer-term *tectonic preconditions*. We would argue, that when viewed on geologically long time scales, tectonics is a major control on the timing of the major glacial periods in Earth's history.

5.1.1. Tectonic preconditions for glaciation

We agree with Crowell's (1999) assertion no 'single cause' is responsible for glaciation in Earth history and that plate tectonics, by determining the geographic distribution of land and water and the elevation of land, is a *preeminent* control on climate. The migrations of tectonic plates create dramatic changes in continental positioning including the latitudinal distribution and extent of landmasses and oceans and eustatic sea level. These large-scale changes to the planet's geography affects thermohaline circulation within the world's oceans, the latitudinal distribution of temperature and global atmospheric circulation patterns (e.g., Worsley and Kidder, 1991). Interoceanic passageways and sills are opened and closed and large fluxes of clastic sediment alter global geochemical fluxes and atmospheric chemistry. Despite these enormous changes, some have seen glaciation as simply being imposed on the planet. Witness the use of the terms 'icehouse' and 'greenhouse' and the notion that the planet passes from one to the other on a regular, repetitive basis controlled by geochemical cycles such as changing CO_2 fluxes (Fischer, 1982, 1984; Nance et al., 1986; Veevers, 1990). In contrast, as knowledge of Earth's plate tectonic history has increased so the imprint of tectonics can be discerned. Phanerozoic glaciation of North Africa and surrounding areas at the end of the *Ordovician* was likely conditioned by broad-scale uplift across the mid-to-high latitude, active margin of the African plate accompanying closure of the Iapetus Ocean (Deynoux et al., 1985). Similarly, *Devonian* glaciation of Bolivia and adjacent areas of Brazil, occurred on uplifted portions of what can be called the 'proto Andes' along the active margin of the South American plate (Caputo, 1985; Diaz-Martinez et al., 1999; Isaacson et al., 1999). Regional Gondwanan uplift accompanying the collision of Laurentia and Gondwana, was a key precursor for late Paleozoic (*Carboniferous–Permian*) glaciations of the southern continents as they drifted across high paleolatitudes (Powell and Veevers, 1987; Eyles, 1993; Crowell, 1999). Drift into polar latitudes, thermal isolation and strong uplift of the Transantarctic Mountains is the background to *Paleogene* inception of glaciation in Antarctica at around 40 Ma or earlier (Berhrendt and Cooper, 1991; Fitzgerald, 1992; Finn et al., 2003). Most recently, the growth of *Pleistocene* continental ice sheets across North America and Europe after 2.5 Ma was the culmination of a long history of tectonically induced paleogeographic and geochemical changes. Key events include uplift of the Himalaya as a result of the collision between India and Asia (Ruddiman and Kutzbach, 1989; Raymo and Ruddiman, 1992), the closure of the Straits of Panama, combined with North Atlantic rifting and uplift of extensive 'magmatically underplated' passive margins in mid-to-high latitudes (Eyles, 1996, 1997; Chalmers and Cloetingh, 2000). Similarly, strong 'preglacial' tectonic uplift is also recorded in the marine record of glaciation in the northeast Pacific (Lagoe et al., 1993; Prueher and Rea, 2001). Whereas astronomical forcing and other variables, such as PCO_2, dictates the precise timing of glacial *events*, Phanerozoic glacial eras sensu lato appear to be preconditioned in the long term, by tectonics and paleogeography.

The proponents of the Snowball Earth model suggest that the Neoproterozoic record of glaciation 'has never fitted comfortably into Phanerozoic stereotypes' (Hoffman and Schrag, 2002, p. 130). In the next section, we test this assertion by focussing on the relationship between tectonics and sedimentation in the Neoproterozoic. We shall demonstrate that Carboniferous–Permian glaciation provide a well-studied analog for the Neoproterozoic.

5.1.2. A late Paleozoic Gondwanan analog for Neoproterozoic glaciated basin fills

Arguably, the best sedimentologic record of late Paleozoic glaciation is preserved along the continental margin of Western Australia (Crowell, 1999). There, thick (up to 4 km) 'glacially influenced' marine strata are preserved in seven large intracratonic basins flanking the sharply faulted margin of the Western Australian shield (Yilgarn–Pilbara blocks). Cold climate strata are represented by glacially influenced shales and diamictites resting on tilted and faulted strata, that record the start of a new tectonic cycle of widespread extension and basin subsidence accompanying the rifting of continental fragments from Australia. Rift- and subduction-related uplift across the high latitude portions of Gondwana was the key development that triggered the formation of regional ice covers during the late Carboniferous (Powell and Veevers, 1987). This explains why the lowermost stratigraphic unit in most Late Paleozoic Gondwana basins is composed of coarse-grained glaciclastic strata implying a direct causal relationship between thermal subsidence, uplift of basin margins and the formation of ice covers on inland plateaux and highlands (Eyles and Eyles, 1993, 2000; Visser and Praekelt, 1996). The total length of the rifted continental margin in Australia is almost 4000 km and thus comparable in scale, with parts of the rifted margin of Rodinia (Fig. 4). A distinct tectonostratigraphic succession can be identified in each Australian basin reflecting the extensional tectonic setting and systematic changes in sedimentation during the rift cycle. The nature of such successions is described below and then applied to the Neoproterozoic record.

5.1.3. Tectonostratigraphic successions in marine rift basins

The tectonostratigraphic evolution of marine rift basin fills is sufficiently well known (e.g., Ravnas and Steel, 1998; Bosence, 1997; Gawthorpe and Leeder, 2000; Halfar et al., 2001; Ledesma and Johnson, 2001) that broad generalisations can now be made.

Rift basin fills commonly show a typical internal tripartite organisation composed of *lowermost* coarse-grained, mass flow-dominated successions (synrift strata forming what Martins-Neto et al., 2001, term a 'tectonosequence'), a *middle* tectonosequence consisting of fine-grained turbidites (recording thermal subsidence) and *uppermost* shallow marine tectonosequence of the postrift phase (Fig. 14). These broadly defined tripartite successions record the changing interplay of subsidence and sediment supply during any one cycle of rifting. Naturally, while these broad subdivisions provide insight into the evolution of basin fills, in reality there may be multiple phases of fault movement and quiescence within any one basin (e.g., Bosence, 1997; Gawthorpe and Leeder, 2000; Martins-Neto et al., 2001).

5.1.3.1. Synrift strata. The initial stage of marine rift basin formation involves listric normal faulting and isostatic compensation and uplift of rift flanks. The associated rejuvenation of relief produces influxes of coarse clastic sediment (Fig. 14). The role of flexural rebound along rifted basin margins in response to erosional unloading can create significant topographic relief with the potential for producing very large volumes of sediment (McGinnis et al., 1993). In western Australia, for example, Braun and Shaw (2001) estimate the total amount of synrift flank uplift and erosion in the Canning Basin was as much as 5 km during one or more Phanerozoic extension events. The close relationship between rift flank uplift involving the formation of large escarpments and sediment supply has been quantitatively modelled (Kooi and Beaumont, 1994; see Merritts and Ellis, 1994 for review).

As a consequence of tectonically enhanced topography and active faulting, a broad family of poorly sorted deposits, such as diamictites, coarse-grained turbidites, olistostromes and megabreccias, dominate synrift strata. Diamictites (together with a wide range of moderately to poorly sorted, clast- to matrix-supported conglomeratic facies) are produced during downslope mass flow of unstable sediment from steep basin margin faults (e.g., Dorsey et al., 2001). During flow, different textural populations become mixed (a process called 'textural inversion' by Nemec and Steel, 1984) to form massive diamictites as debris flows much in the fashion of a cement mixer (Eyles and Eyles, 2000). The 'pebbly muds' of Crowell (1957), 'mixtites' of Schermerhorn (1966, 1974a) and 'compound mass movements' of Einsele (2000) are formed in this fashion. Associated 'megabreccias' record large catastrophic landslides released from steep footwall slopes (e.g., Yarnold and Lombard, 1989; Bentham et al., 1991; Sengör, 1995). A great variety of deformation structures resulting from liquefaction during strong seismicity are also produced. Early synrift strata show marked lateral facies variability reflecting a diverse topography of isolated half grabens and complex sediment pathways (Einsele, 2000). The abundance of coarse debris, poor textural sorting of many facies and presence of penetrative deformation structures in rapidly deposited and seismically disturbed synrift successions, all lend themselves to 'glacial' misinterpretation by past workers.

5.1.3.2. Thermal subsidence phase. Tectonic subsidence rates attain their maximum value in marine rift basins after the initial phase of faulting. This is the result of strong thermal subsidence and results in the creation of larger basins. At this time, basin margins and source areas are flooded and turbidite shale units accumulate offshore creating a widespread and overlapping blanket of fine-grained facies on top of synrift facies (Fig. 14). The sedimentary effects of eustatic sea-level change during this phase are easily suppressed by rapid subsidence. Ravnas and Steel (1998) specifically cautioned against assigning time- and sequence-stratigraphic significance to shale intervals in rift basins acknowledging that deposition is diachronous both within individual basins and between basins. Detailed biostratigraphic data from Western Australia show that similar facies were deposited diachronously from one basin to another along the length of the rifted margin (Eyles et al., 2002). This is in marked contrast to the assumptions of previous workers who regarded shales as globally correlative glacioeustatic 'event markers' recording synchronous deglaciation events across Gondwana (Visser, 1997; Golonka and Ford, 2000).

5.1.3.3. Post rift phase. A final postrift stage in marine rift basin fills results from a marked reduction in subsidence rates which allows the 'oversupply' and progradation of nearshore fluvial and deltaic wedges including carbonates. This is recorded by shallow marine facies successions deposited in high-energy nearshore settings (e.g., Dorsey et al., 2001, Fig. 14). Carbonates are a common component (e.g., Halfar et al., 2001). Given reduced rates of tectonic subsidence, the postrift stratigraphy has the potential to record clear evidence of eustatically driven changes in water depths.

5.1.4. Application of the tectonostratigraphic model to Neoproterozoic basins during Rodinian breakup

Schermerhorn (1974a, 1983) proposed a tectonostratigraphic model for Neoproterozoic diamictite-bearing successions similar to that being proposed here. He emphasised the importance of rifting, source area uplift and shedding of poorly sorted debris to rapidly subsiding marine basins. He argued that glaciation only occurred in those latitudes where source area uplift exceeded the elevation of the snowline. The model inherently recognised first, that Neoproterozoic glaciation was regional in extent and controlled by elevation and latitude, and second, that tectonics governed the nature of the deposits. Martin et al.

(1985), Eyles (1993) and Brookfield (1994) tested and confirmed this model and stressed the overriding control of tectonic setting on the global preservation and type of Neoproterozoic glacial deposits. Schermerhorn recognised the existence of 'megacycles' that could be broadly correlated from Australia to China to North America, that in hindsight, are 'tectonostratigraphic successions'. Young (1992a, 1995) extended this concept and emphasised that such successions were related to the breakup of Rodinia and thus could be correlated from one rifted margin to another, on either side of the current Pacific Ocean. They are thus similar to Jurassic 'breakup' tectonostratigraphic successions deposited either side of the current Atlantic Ocean during its earliest history and that are *broadly* correlative from one opposed margin to another (Cloetingh et al., 1989).

The simplified and highly idealized tripartite tectonostratigraphic succession typical of marine rift basins can be seen in many Neoproterozoic 'glacial' successions in Australia, North America, Oman, Scandinavia and China. Diamictites and other coarse-grained sediment gravity flow facies are present as lowermost synrift facies and are overlain by thick turbidite 'blankets' that coarsen upwards into shallow water platformal facies (see Figs. 6, 6, 12, 13 and 14). Some basins contain single tectonostratigraphic successions, others multiple, superposed successions; the great length of the rifted margin guarantees that rifting and deposition was diachronous across Rodinia. We propose that rift-related tectonostratigraphic successions were deposited *at different times* as Rodinia became progressively 'unzipped' after ca. 750 Ma by two large 'megarift' systems that developed along the western and eastern margins of Laurentia (Fig. 4A,B). By analogy with the formation of the Atlantic Ocean, the duration of rifting varied from one part of the rift system to another and rifting was markedly diachronous (e.g., Ziegler, 1989). If it is accepted that Neoproterozoic glaciation is rift-related, then also it was diachronous and not globally instantaneous (e.g, Deynoux et al., 1978). This model we call 'Zipper-rift'.

In areas where elevation or latitude were insufficient to allow glaciation, rift basin fills and associated diamictic synrift facies are entirely nonglacial as Schermerhorn (1974a) stressed. Rather than global refrigeration implied by the 'Snowball Earth' model, Neoproterozoic glaciation was likely restricted to those areas where latitude, elevation and a suitable supply of moisture combined to allow ice covers to grow on uplifted rift flanks and plateaux. Because of the diachronous progression of rifting across Rodinia, glacial strata, where correctly identified, may reflect the time transgressive, regional growth of ice centres and are unlikely to be global chronostratigraphic marker horizons. It is also quite possible that crustal uplift, combined with a lowered snowline elevation resulting from a reduced solar constant, may have combined to generate ice covers at latitudes lower than that during Phanerozoic glaciations.

It is a major limitation of the 'Zipper-rift' model that the existing chronostratigraphic database is insufficient to validate the model. In addition, it is very likely that significant gaps occur in the Neoproterozoic glacial record. Many millions of years of initial glaciation on uplifting source areas likely went unrecorded as rift basins evolved and preexisting cratonic sediment was cannibalised and reworked. The strength of the model is that it underscores the strong linkages between the Neoproterozoic sedimentary record of glaciation and basin tectonics.

5.1.4.1. Neoproterozoic rifting and glaciation; a role for mantle plumes? Several authors have invoked mantle plumes as a cause of the breakup of Rodinia (Zhao et al., 1994; Li et al., 1999; Torsvik et al., 1996; Martins-Neto, 1998; Pirajno, 2000) similar to the role played much later by mantle processes in the doming and fragmentation of Gondwana (e.g., Storey, 1995; Honda et al., 2000). The Neoproterozoic of Australia provides an example of the close relationship between plumes and regional climatic response. The plate tectonic setting of Sturtian strata in Australia closely resembles a large triple junction (Karlstrom et al., 1999) possibly reflecting the presence of hot mantle upwelling below (Zhao et al., 1994; Li et al., 1999; Pirajno, 2000; Williams and Gostin, 2000). The ca. 750 Ma rift margin between Laurentia and Australia/Antarctica opened to form the paleo-Pacific Ocean and is partnered by a series of en echelon basins (Officer, Amadeus) that together comprised a complex failed rift system propagating into central and western Australia. Williams and Gostin (2000) summarized evidence for a mantle plume highlighting the presence of widespread flood basalts in northern (Antrim Plateau Volcanics) and southern Australia (Table Hill

Volcanics) with correlative events recorded in Antarctica (see Goodge et al., 2002). While the timing of uplift across this region of Rodinia is poorly constrained, the sedimentology and stratigraphy of the thick sediment gravity flow-dominated successions in the Officer and Adelaide basins is indicative of an active rift setting and extremely rapid rates of subsidence and sediment supply (Section 4.1.1).

The doming of continental lithosphere above mantle plumes and large hot spots is well documented by Tertiary uplifts of as much as 3000 m in Antarctica (LeMasurier and Landis, 1996) and around the margins of the North Atlantic Ocean (Wood et al., 1989; Vagnes and Amundsen, 1993; Eyles, 1996; Dam et al., 1998; Japsen and Chalmers, 2000). The latter gave rise to the characteristic circum-North Atlantic landscape of uplifted plateaux and deep, structurally controlled, glacially overdeepened troughs (fiords).

5.1.4.2. Implications for high obliquity models. Some workers have interpreted evidence of Neoproterozoic glaciation along the equator in terms of Earth's changing obliquity. They argue that high (>54°) angle of obliquity during the Proterozoic changed to the present value (23°) at the end of the Neoproterozic (Williams, 1975, 1993, 1994, 2000; Williams et al., 1998). Discussion of the geophysical merits of this hypothesis is beyond the scope of this present paper (but see Hoffman and Maloof, 2001). We only note that the model is based on the assumption that continental ice sheets and seasonally cold climates existed at the equator and thus suffers essentially from the same limitations as does the Snowball Earth model.

5.1.4.3. Results of general circulation modelling. The implausibility of a completely frozen Snowball Earth has been emphasised by climate modellers (Hyde et al., 2000). Others have similarly pointed out the thermal difficulty of creating frozen oceans at low latitudes (Crowley and Hyde, 2001; Baum and Crowley, 2001). General circulation modelling cannot replicate a completely permafrozen Earth, but instead predicts a 'normal' planet that is ice-free at paleolatitudes lower than 25° (the so-called 'slushball Earth' of Schrag and Hoffman, 2001). In regard to modelling of *Phanerozoic* climates, Boucot and Gray (2001, p. 135) concluded that global climatic gradients are fundamentally dependent on changing land mass and continental positioning. They stressed the need to incorporate information regarding the 'location(s) through time of major upland regions. . .and information about major landmass positions' (e.g., Worsley and Kidder, 1991; Worsley et al., 1994). Next-generation Neoproterozoic climate models are being developed that will incorporate new data on rift-generated Rodinian tectonotopography and the associated climatic response (W.R. Peltier, personal communication, 2002).

6. Conclusion

(1) The hypothesis of global Neoproterozoic permafrost and catastrophic, instantaneous glaciation ('Snowball Earth') is difficult to reconcile with the sedimentological and stratigraphic database. The major weakness of the model of global glaciation, as was first identified by L.M.G. Schermerhorn in the mid-1970s, is that of oversimplified interpretations of the origin, distribution and age of diamictites; that is, that they are tillites and because of their presence on all continents were deposited synchronously by global ice sheets.

(2) Not all Neoproterozoic diamictites are tillites. Neoproterozoic diamictites are overwhelmingly, the product of tectonically related, nonglacial, subaqueous mass flow processes in marine basins. Diamictites occur within thick turbidite-dominated, 'synrift' successions in predominantly rift basins. Some do indeed reveal a record of a glacial influence on sedimentation indicating a supply of glacigenic sediment to marine (and lacustrine) rift basins. Tillites and associated terrestrial facies, deposited directly below ice sheets on exposed land surfaces, were rarely preserved on stable craton surfaces; the stratigraphic record of glaciation is biased toward offshore marine deposits. The key to the genetic interpretation of Neoproterozoic diamictite facies is their sedimentary, stratigraphic and tectonic context.

(3) Mapping of glacially influenced strata across Rodinia indicates a close association between rifting and glaciation. Neoproterozoic glaciation was likely diachronous, regional in scope and tectonically preconditioned as a result of the breakup of Rodinia. Ice covers were probably no more extensive than their later Phanerozoic counterparts; several glacially influenced marine successions appear to have nonglacial marine correlatives indicating limited influence of ice.

The location of ice centres appears to have been primarily controlled by rift (and mantle plume?)-related topographic uplift. Glacially influenced successions likely formed diachronously during Rodinian megarifting between 750 Ma when the paleo-Pacific Ocean opened and about 610 Ma during initial opening of the Iapetus (paleo-Atlantic Ocean). The first group includes the Sturtian deposits of western North America and Australia; the youngest includes the Marinoan and Vendian strata of Australia and northwest Europe, respectively. Diachronous, tectonically preconditioned climate change may explain still younger ice centres (post 590 Ma) recorded in the cratonic Kimberley district of northwest Australia and those of the circum-Atlantic Cadomian Belt associated with volcanic arc settings.

(4) The precise origin of cap carbonates is not well understood and detailed studies where available, do not record abrupt and extreme, postglacial environments postulated by the Snowball model. Additional detailed petrographic and stratigraphic studies are required. Neoproterozoic rift basin successions contain large volumes of clastic carbonate reworked from faulted carbonate platforms and complicates identification of 'cap carbonates'. The latter term has been used liberally in the Snowball literature, to refer to primary carbonate strata lying unconformably, and stratigraphically well above clastic synrift strata below.

(5) The paleomagnetic database on which the notion of low-latitude glaciation is based is not robust. The sedimentology, origin and age of key paleomagnetic stratotypes in Australia and northwest Canada requires additional investigation.

(6) Given the regional and diachronous nature of Neoproterozoic glaciations, extreme shifts in C-isotope values in late Neoproterozoic strata are unlikely to be the product of global refrigerations that shut down the planet's hydrological and biological systems. Global biological crises triggered by global permafrost are not evident in the biological record. Any link between worldwide glaciation and later postglacial sea-level rise with the Cambrian 'explosion' of skeletized metazoans is not indicated. Stratigraphic evidence for regional ice covers, together with the results of general circulation modelling, indicate eustatic sea-level fluctuations arising from Neoproterozoic glaciations were likely in the range of those due to Phanerozoic glaciations (70–150 m).

(7) The Neoproterozoic glacial sedimentary record indicates a normal, fully functioning hydrological system, involving open oceans, the production of large volumes of clastic sediment from upland source areas and their delivery to sedimentary basins by water and gravity. Sedimentary facies are readily interpreted by reference to well-known Phanerozoic depositional 'stereotypes'. Sedimentological evidence indicates no need to suspend the application of uniformitarian principles that hitherto have served geologists so well in other parts of Earth's glacial record.

(8) The tectonic 'Zipper-rift' model presented here as an explanation for Neoproterozoic glacials during the protracted breakup of Rodinia after 750 Ma is no doubt simplistic dependent as it is on a rapidly changing understanding of the history of Rodinia. Regardless, the key finding of this paper has been that there is overwhelming evidence of a strong link between tectonics, facies types and successions in what were tectonically active basins. This stratigraphic record can no longer be interpreted in classic bed-for-bed style as a direct 'bed-for-bed' record of climate or eustatic sea level.

Acknowledgements

The research on which this paper is based was made possible by several grants from the Natural and Engineering Research Council of Canada to Eyles and a doctoral scholarship to Januszczak. We thank Karl-Heinz 'Charlie' Hoffmann at the Geological Survey of Namibia in Windhoek and Paul Hoffman for discussions and logistical help with access to key outcrops in Namibia. We have enjoyed very fruitful discussions with Emmanuelle Arnaud, Carolyn Eyles, Kath Grey, Andrew Miall, Richard Hyde and Noel James. In particular, we are very grateful to Andrew Miall, Dick Peltier, John Crowell and David Evans for their helpful critical comments on earlier versions of the manuscript.

References

Abolins, M.J., Charlton, R., Wernicke, B.P., Ripperdan, R.L., 1999. Three distinct Neoproterozoic glacial intervals recorded in western Laurentia and Australia. Abstr. Programs - Geol. Soc. Am. 31, 485.

Abolins, M., Oskin, R., Prave, T., Summa, C., Corsetti, F., 2000. Neoproterozoic glacial record in the Death Valley region, California and Nevada. Geol. Soc. Am. Field Guide 2, 319–335.

Abrahamsen, N., 1998. Paleomagnetic results from Greenland and Denmark. In: Richard, J., Michelsen, O. (Eds.), Geoscience in Aarhus. Aarhus University, Aarhus, pp. 21–25.

Agassiz, L., 1840. Etudes sur les glaciers. Privately published, Neuchatel, Switzerland.

Agassiz, L., 1842. The ice period; a period of history of our globe. Sel. Period. Lit. Foreign Ctries. 3, 307–326.

Agassiz, L., 1866. Traces of Glaciers under the Tropics. Unpublished paper read before the National Assembly of Sciences, Washington, DC, August 12th.

Agassiz, L., 1876. Geological Sketches, 2nd series. J.R. Osgood and Co., Boston, pp. 153–229.

Agassiz, E.C., 1886. Louis Agassiz, His Life and Correspondence, vol. 11. Houghton, Mifflin and Co., Boston, p. 639.

Agassiz, L., Coutinho, J.M.da Silva, 1868. Sur la geologie de L'Amazone. C. R. Acad. Sci. Paris 64, 1269–1271.

Aitken, J.D., 1989. A "sea level" curve for the terminal Proterozoic, Mackenzie Mountains, N.W.T.; progress report. Geol. Assoc. Can., Progr. Abstr. 14, 99.

Aitken, J.D., 1991a. The Ice Brook formation and Post-Rapitan Late Proterozoic glaciation, Mackenzie Mountains, Northwest Territories. Bull. - Geol. Surv. Can. 404, 1–43.

Aitken, J.D., 1991b. Two Late Proterozoic glaciations, Mackenzie Mountains, northwestern Canada. Geology 19, 445–448.

Aldiss, B.A., 1985. Helliconia-Winter. Jonathan Cape, New York. ISBN: 0224018477, 392 pp.

Alley, R.B., 2000. The Two Mile Time Machine: Ice Cores, Abrupt Climate Change, and Our Future. Princeton Univ. Press, Princeton, NJ, 229 pp.

Anderson, J.B., 1983. Ancient glacial–marine deposits: their spatial and temporal distribution. In: Molnia, B.F. (Ed.), Glacial–Marine Sedimentation. Plenum, New York, pp. 3–92.

Anderson, J.B., 1999. Antarctic Marine Geology. Cambridge Univ. Press, Cambridge, 289 pp.

Arnaud, E., Eyles, C.H., 2002. Catastrophic mass failure of a Neoproterozoic glacially-influenced continental margin, the Great Breccia, Port Askaig Formation, Scotland. Sediment. Geol. 151, 313–333.

Baum, S.K., Crowley, T.J., 2001. GCM response to Late Precambrian (~ 590 Ma) ice-covered continents. Geophys. Res. Lett. 28, 583–586.

Bekker, A., Eriksson, K.A., Kaufman, A.J., Karhu, J.A., Beukes, N.J., 1999. Paleoproterozoic record of biogeochemical events and ice ages. Abstr. Programs - Geol. Soc. Am. 31, 487.

Bengsten, S. (Ed.), 1994. Early Life on Earth-Nobel Symposium No. 84. Columbia Univ. Press, New York.

Benn, D.I., Evans, D.J.A., 1998. Glaciers and Glaciation. Arnold, London, 734 pp.

Bennett, M.R., Huddart, D., Thomas, G.S.P., 2002. Facies architecture within a regional glaciolacustrine basin: Copper River, Alaska. Quat. Sci. Rev. 21, 2237–2280.

Bentham, P., Collier, R.E.L., Gawthorpe, R.L., Leeder, M.R., Prosser, S., Stark, C., 1991. Tectono-sedimentary development of an extensional basin: the Neogene Megara basin, Greece. J. Geol. Soc. (Lond.) 148, 923–934.

Benus, A.P., 1988. Deep-water outer fan and slope sedimentation in a late Precambrian Avalonian basin. Abstr. Programs - Geol. Soc. Am. 20, 6.

Benvenuti, M., 2003. Facies analysis and tectonic significance of lacustrine fan deltaic successions in the Pliocene–Pleistocene Mugello Basin, Central Italy. Sediment. Geol. 157, 197–234.

Berhrendt, J.C., Cooper, A.K., 1991. Evidence of rapid Cenozoic uplift of the rift shoulder escarpment of the Cenozoic West Antarctic rift system and a speculation on possible climate forcing. Geology 19, 360–363.

Bidgood, D.E.T., Harland, W.B., 1961a. Palaeomagnetic studies of some Greenland rocks. Geology of the Arctic. University of Toronto Press, Toronto, pp. 285–292.

Bidgood, D.E.T., Harland, W.B., 1961b. Paleomagnetism in some East Greenland sedimentary rocks. Nature 189, 633–634.

Bingen, B., Demaiffe, D., van Breemen, O.V., 1998. The 616 Ma old Egersund basaltic dike swarm, SW Norway and late Neoproterozoic opening of the Iapetus Ocean. J. Geol. 106, 565–574.

Bolles, E.B., 1999. The Ice Finders. Counterpoint, Washington, DC, 257 pp.

Bond, G., Heinrich, H., Broecker, W.S., Labeyrie, L.D., MsManus, J., Andrews, J., Huon, S., Jantschik, R., Clasen, S., Simet, C., Tedesco, K., Klas, M., Bonani, G., Ivy, S., 1992. Evidence for massive discharges of icebergs into the North Atlantic during the last glacial period. Nature 360, 245–249.

Bosence, D.W.J. (Ed.), 1997. Special Issue on Mesozoic Rift Basins of Yemen. Mar. Pet. Geol., vol. 14, pp. 611–730.

Boucot, A.J., Gray, J., 2001. A critique of Phanerozoic climatic models involving changes in the CO_2 content of the atmosphere. Earth-Sci. Rev. 56, 1–160.

Boulton, G.S., 1972. Modern arctic glaciers as depositional models for former ice sheets. J. Geol. Soc. (Lond.) 128, 361–393.

Boulton, G.S., 1978. Boulder shapes and grain size distributions of debris as indicators of transport paths through a glacier and till genesis. Sedimentology 25, 773–799.

Boulton, G.S., 1996. Theory of glacial erosion, transport and deposition as a consequence of subglacial sediment deformation. J. Glaciol. 42, 43–62.

Boulton, G.S., Dobbie, K.E., 1998. Slow flow of granular aggregates: the deformation of sediments beneath glaciers. Philos. Trans. R. Soc. Lond., A 356, 2713–2745.

Boulton, G.S., Eyles, N., 1979. Sedimentation by valley glaciers; a model and genetic classification. INQUA Symposium on Genesis and Lithology of Quaternary Deposits, Sept. 1978, pp. 11–23.

Boulton, G.S., Dobbie, K.E., Zatsepin, S., 2001. Sediment deformation beneath glaciers and its coupling to the subglacial hydraulic system. Quat. Int. 86, 3–28.

Boyce, J.I., Eyles, N., 2000. Architectural element analysis applied to glacial deposits; internal geometry of a Late Pleistocene till sheet, Ontario, Canada. Geol. Soc. Am. Bull. 112, 98–118.

Branner, J.C., 1893. The supposed glaciation of Brazil. J. Geol. 1, 753–772.

Brasier, M.D., Lindsay, J.F., 2000. Did supercontinent amalgamation trigger the "Cambrian explosion"? In: Zhuralev, A., Riding, R. (Eds.), The Ecology of the Cambrian Radiation. Columbia Univ. Press, New York, pp. 69–89.

Brasier, M.D., Dorjnamjaa, D., Lindsay, J.F., 1996a. The Neoproterozoic to early Cambrian in southwest Mongolia: an introduction. Geol. Mag. 133, 365–369.

Brasier, M.D., Shields, G., Kuleshov, V.N., Zhegallo, E.A., 1996b. Intergrated chemo- and biostratigraphic calibration of early animal evolution: Neoproterozoic–early Cambrian of southwest Mongolia. Geol. Mag. 133, 445–485.

Braun, J., Shaw, R., 2001. A thin-plate model of Palaeozoic deformation of the Australian lithosphere: implications for understanding the dynamics of intracratonic deformation. In: Miller, J.A., Holdsworth, R.E., Buick, I.S., Hand, M. (Eds.), Continental Reactivation and Reworking. Geological Society Special Publications, vol. 184. Geological Society of London, London, pp. 165–193.

Broecker, 1994. Massive iceberg discharges as triggers for global climate change. Nature 372, 421–424.

Brookfield, M.E., 1994. Problems in applying preservation, facies and sequence models to Sinian (Neoproterozoic) glacial sequences in Australia and Asia. Precambrian Res. 70, 113–143.

Brooks, C.E.P., 1949. Climate Through the Ages, 2nd ed. McGraw Hill Book, New York, 395 pp.

Budyko, M., 1969. The effect of solar radiation variations on the climate of the Earth. Tellus 21, 611–619.

Budyko, M.I., 1982. The Earth's Climate: Past and Future. Academic Press, 307 pp.

Budyko, M., 1999. Climate catastrophes. Glob. Planet. Change 20, 281–288.

Caldeira, K., Kasting, J.F., 1992. Susceptibility of the early Earth to irreversible glaciation caused by carbon dioxide clouds. Nature 359, 226–228.

Calver, C.R., 1998. Isotope stratigraphy of the Neoproterozoic Togari Group, Tasmania. Aust. J. Earth Sci. 45, 865–874.

Caputo, M.V., 1985. Late Devonian glaciation in South America. Palaeogeogr. Palaeoclimatol. Palaeoecol. 51, 291–317.

Carozzi, A.V., 1966. Agassiz's amazing geological speculation; the Ice Age. Stud. Romant. 2, 57–83.

Carozzi, A.V., 1967. In: Carozzi, A.V. (Ed.), Studies on Glaciers. Hafner Publishing, New York, 213 pp.

Carozzi, A.V., 1974. Agassiz's influence on geological thinking in the Americas. Arch. Sci. Soc. Phys. Hist. Nat. Geneve 27, 5–38.

Cawood, P.A., McCausland, P.J.A., Dunning, G.R., 2001. Opening Iapetus: constraints from the Laurentian margin in Newfoundland. Geol. Soc. Am. Bull. 113, 443–453.

Chalmers, J.A., Cloetingh, S., 2000. Neogene uplift and tectonics around the North Atlantic. Glob. Planet. Change 24, 165–318.

Christie-Blick, N., 1983. Glacial-marine and subglacial sedimentation, upper Proterozoic Mineral Fork Formation, Utah. In: Molnia, B.F. (Ed.), Glacial Marine Sedimentation. Plenum, New York, pp. 703–766.

Christie-Blick, N., 1997. Neoproterozoic sedimentation and tectonics in west-central Utah. Brigham Young University, Geol. Stud. 42, 1–30.

Christie-Blick, N., Grotzinger, J.P., von der Borch, C.C., 1988. Sequence stratigraphy in Proterozoic successions. Geology 16, 100–104.

Christie-Blick, N., Dyson, I.A., von der Borch, C.C., 1995. Sequence stratigraphy and the interpretation of Neoproterozoic Earth history. Precambrian Res. 73, 3–26.

Chumakov, N.M., 1981. Upper Proterozoic glaciogenic rocks and their stratigraphic significance. Precambrian Res. 15, 373–395.

Chumakov, N.M., 1985. Glacial events of the past and their geological significance. Palaeogeogr. Palaeoclimatol. Palaeoecol. 51, 319–346.

Cloetingh, S., Tankard, A.J., Welsink, H.J., Jenkins, W.A.M., 1989. Vails' coastal onlap curves and their correlation with tectonic events, offshore eastern Canada. In: Tankard, A.J., Balkwill, H.R. (Eds.), Extensional Tectonics and Stratigraphy of the North Atlantic Margins. Mem. - Am. Assoc. Pet. Geol. 46, 283–294.

Coleman, A.P., 1907. A lower Huronian ice age. Am. J. Sci. 23, 187–192.

Coleman, A.P., 1916. Dry land in geology. Geol. Soc. Am. Bull. 27, 175–192.

Coleman, A.P., 1926. Ice Ages: Recent and Ancient. Macmillan, London, 296 pp.

Coleman, A.P., 1929. Long range correlation of varves. J. Geol. 37, 783–789.

Coleman, A.P., 1932. Glaciation and continental drift. Geogr. J. LXXIX, 252–255.

Coleman, A.P., 1939. Ice ages in the geological column. Geol. Soc. Am. Bull. 50, 449–452.

Coleman, A.P., 1941. The Last Million Years. AMS Press, New York, 216 pp.

Collinson, J.D., Bevins, R.E., Clemmensen, L.B., 1989. Postglacial mass flow and associated deposits preserved in paleovalleys: the late Precambrian Moraeneso formation, North Greenland. Medd. Gronl., Geosci. 21 (26 pp.).

Condon, D.J., Prave, A.R., Benn, D.I., 2002. Neoproterozoic glacial-rainout intervals: observations and implications. Geology 30, 35–38.

Coniglio, M., Dix, G.R., 1992. Carbonate slopes. In: Walker, R.G., James, N.P. (Eds.), Facies Models: Response to Sea Level Change. Geological Association of Canada, St. John's, pp. 349–373.

Corkeron, M.L., George, A.D., 2001. Glacial incursion on a Neoproterozoic carbonate platform in the Kimberley region, Australia. Geol. Soc. Am. Bull. 113, 1121–1132.

Corsetti, F.A., Kaufman, A.J., 1999. Tossing Neoproterozoic snowballs between Death Valley, USA and Namibia: a comparison of unique post-glacial facies and carbon isotopic trends. Abstr. Programs - Geol. Soc. Am. 31, 486.

Cotton, C.A., 1942. Climatic Accidents in The Landscape. Whitcombe & Tombs, New Zealand, 354 pp.

Crawford, A.R., Daily, B., 1971. Probable non-synchoneity of late Precambrian glaciations. Nature 230, 111–112.

Croll, J., 1867. On the eccentricity of the Earth's orbit and its physical relations to the glacial epoch. Philos. Mag. 33, 119–131.

Crossing, A.R., Gostin, V.A., 1994. Isotopic signatures of carbonates associated with Sturtian (Neoproterozoic) glacial facies, central Flinders Ranges, South Australia. In: Deynoux, M.M., Miller, J.M.G., Domack, E.W., Eyles, N., Fairchild, I.J., Young, G.M. (Eds.), Earth's Glacial Record. Cambridge Univ. Press, New York, pp. 165–175.

Crowell, J.C., 1957. Origin of pubbly mudstone. Bull. Geol. Soc. Am. 68, 993–1010.

Crowell, J.C., 1983. Ice ages recorded on Gondwanan continents. Trans. Geol. Soc. S. Afr. 86, 262–273.

Crowell, J.C., 1999. Pre-Mesozoic ice ages: their bearing on understanding the climate system. Mem. Geol. Soc. Am. 192, 106.

Crowley, T.J., Hyde, W.T., 2001. CO_2 levels required for deglaciation of a ''Near-Snowball'' Earth. Geophys. Res. Lett. 28, 283–286.

Dalrymple, R.W., Narbonne, G.M., 1996. Continental slope sedimentation in the Sheepbed Formation (Neoproterozoic, Windermere Supergroup), Mackenzie Mountains, N.W.T. Can. J. Earth Sci. 33, 848–862.

Dalziel, I.W., 1991. Pacific margins of Laurentia and East Antarctica–Australia as a conjugate rift pair: evidence and implications for an Eocambrian supercontinent. Geology 19, 598–601.

Dalziel, I.W., 1997. Neoproterozoic–Paleozoic geography and tectonics: review, hypothesis, environmental speculation. Geol. Soc. Am. Bull. 109, 16–42.

Dalziel, I.W., Mosher, S., Gahagan, L.M., 2000. Laurentia–Kalahari collision and the Assembly of Rodinia. J. Geol. 108, 499–513.

Dam, G., Larsen, M., Sønderholm, M., 1998. Sedimentary response to mantle plumes: implications from Paleocene onshore succession, West and East Greenland. Geology 26, 207–210.

Davis, G.M., 1908. Causes of Permo-Carboniferous glaciation. J. Geol. 16, 79–82.

De Geer, G., 1926. On the solar curve as dating the ice ages, the New York Moraine and Niagara Falls through the Swedish timescale. Geogr. Ann. 8, 253–283.

Dehler, C.M., Elrick, M., Karlstrom, K.E., Smith, G.A., Crossey, L.J., Timmons, J.M., 2001. Neoproterozoic Chuar Group (approximately 800–742 Ma), Grand Canyon; a record of cyclic marine deposition during global cooling and supercontinent rifting. Sediment. Geol. 141–142, 465–499.

De Kock, W.P., Gevers, T.W., 1933. The Chuos tillite in the Rehoboth and Windhoek districts, South-West Africa. Trans. Geol. Soc. S. Afr. 35, 115–118.

Deynoux, M., 1985. Terrestrial or waterlain glacial diamictites? Three case studies from the late Precambrian and Late Ordovician glacial drifts in West Africa. Palaeogeogr. Palaeoclimatol. Palaeoecol. 51, 97–141.

Deynoux, M., Trompette, R., 1981. Late Ordivician tillites of the Taoudeni Basin, West Africa. In: Hambrey, M.J., Harland, W.B. (Eds.), Earth's Pre-Pleistocene Glacial Record. Cambridge Univ. Press, New York, pp. 89–96.

Deynoux, M., Trompette, R., Schermerhorn, L.J.G., 1976. Late Precambrian mixtites; glacial and/or nonglacial? Dealing especially with the mixtites of West Africa. Am. J. Sci. 276, 1302–1315.

Deynoux, M., Trompette, R., Clauer, N., Sougy, J., 1978. Upper Precambrian and lowermost Palaeozoic correlations in West Africa and in the western part of central Africa. Probable diachronism of the Late Precambrian tillite. Geol. Rundsch. 67, 615–630.

Deynoux, M., Sourgy, J., Trompette, R., 1985. Lower Paleozoic of west Africa and the western part of central Africa. In: Holland, C.H. (Ed.), Lower Paleozoic of The North-Western and West-Central Africa. Lower Paleozoic Rocks of the World, vol. 4. Wiley, Chichester, pp. 337–495.

Deynoux, M., Kocurek, G., Proust, J.N., 1989. Late Proterozoic periglacial aeolian deposits on the west African platform, Taoudeni Basin, western Mali. Sedimentology 36, 531–549.

Deynoux, M., Proust, J.N., Simon, B., 1991. Late Proterozoic glacially controlled shelf sequences in Western Mali, (West Africa). J. Afr. Earth Sci. 12, 181–198.

Diaz-Martinez, E., Vavrdova, M., Bek, M., Isaacson, P.E., 1999. Late Devonian (Famennian) glaciation in Western Gondwana: evidence from the Central Andes. Palaeoclimatol. Abh. Geol. B.-A. (Germany) 54, 1–463.

Dickinson, W.R., 1991. Tectonic setting of faulted Tertiary strata associated with the Catalina core complex in southern Arizona. Geol. Soc. Am. Spec. Pap. 264, 106 pp.

Dionne, J.C., 1993. Sediment load of shore ice and ice rafting potential, Upper St. Lawrence Estuary, Quebec, Canada. J. Coast. Res. 9, 628–646.

Dore, F., Dupret, L., LeGall, J., 1985. Tillites and tilloids of the Armorican Massif. Palaeogeogr. Palaeoclimatol. Palaeoecol. 51, 85–96.

Dorsey, R.J., Umhoefer, P.J., Ingle, J.C., Mayer, L., 2001. Late Miocene to Pliocene stratigraphic evolution of northeast Carmen Island, Gulf of California: implications for oblique-rifting tectonics. Sediment. Geol. 144, 97–123.

Dott, R.H., 1961. Squantum ''Tillite'', Massachusetts; evidence of glaciation or subaqueous mass movements? Geol. Soc. Am. Bull. 72, 1289–1306.

Dowdeswell, J.A., Whittington, R.J., Marienfeld, P., 1994. The origin of massive diamicton facies by iceberg rafting and scouring, Scoresby Sund, east Greenland. Sedimentology 41, 21–35.

Dreimanis, A., 1983. Quaternary glacial deposits; implications for the interpretation of Proterozoic glacial deposits. Mem. Geol. Soc. Am. 161, 299–307.

Drexel, J.F., Preiss, W.V., Parker, A.J., 1993. Geology of South Australia 1: the Precambrian. Geol. Surv. South Aust. Bull. 54 (242 pp.).

Duerr, S.B., Dingledey, D.P., 1997. Tale of three cratons: tectonostratigraphic anatomy of the Damara Orogen in northwestern Namibia and the assembly of Gondwana: discussion. Geology 25, 1149–1151.

DuToit, A.L., 1921. Land connections between the other continents and South Africa in the past. S. Afr. J. Sci. 18, 120–140.

Edwards, M.B., 1975. Glacial retreat sedimentation in the Smalfjord Formation, late Precambrian, North Norway. Sedimentology 22, 75–94.

Edwards, M.B., 1984. Sedimentology of the Upper Proterozoic glacial record, Vestertana group, Finmark, North Norway. Nor. Geol. Unders. 394, 1–76.

Einsele, G., 2000. Sedimentary Basins; Evolution, Facies, and Sediment Budget. Springer, Berlin, 792 pp.

Eisbacher, G.H., 1981. Sedimentary tectonics and glacial record in the Windermere Supergroup, Mackenzie Mountains, northwestern Canada. Spec. Pap. - Geol. Surv. Can. 80-27, 40 pp.

Eisbacher, G.H., 1985. Late Proterozoic rifting, glacial sedimentation and sedimentary cycles in the light of Windermere deposition, Western Canada. Palaeogeogr. Palaeoclimatol. Palaeoecol. 51, 231–254.

Evans, D.A.D., 1999. A Proterozoic Palaeoclimatic Paradox Persists. Tectonics Special Research Center, Annual Report, pp. 63–64.

Evans, D.A.D., 2000. Stratigraphic, geochronological, and paleomagnetic constraints upon the Neoproterozoic climatic paradox. Am. J. Sci. 300, 347–433.

Evans, D.A.D., Zhuravlev, A.Yu., Budney, C.J., Kirschvink, J.L., 1996. Palaeomagnetism of the Bayan Gol Formation, western Mongolia. Geol. Mag. 133, 487–496.

Evans, J.A., Fitches, W.R., Muir, R.J., 1998. Laurentian clasts in a Neoproterozoic tillite from Scotland. J. Geol. 106, 361–366.

Evans, D.A.D., Li, Z.X., Kirschvink, J.L., Wingate, T.D., 2000. A high quality mid-Neoproterozoic paleomagnetic pole from South China, with implications for ice ages and the breakup configuration of Rodinia. Precambrian Res. 100, 313–334.

Eyles, C.H., Eyles, N., 1983. Sedimentation in a large lake: a reinterpretation of the late Pleistocene stratigraphy at Scarborough Bluffs, Ontario, Canada. Geology 11, 146–152.

Eyles, C.H., Eyles, N., 2000. Subaqueous mass flow origin for Lower Permian diamictites and associated facies of the Grant Group, Barbwire Terrace, Canning Basin, Western Australia. Sedimentology 47, 343–356.

Eyles, C.H., Eyles, N., Franca, A.B., 1993. Glaciation and tectonics in an active intracratonic basin: the Late Palaeozoic Itararé Group, Paraná Basin, Brazil. Sedimentology 40, 1–25.

Eyles, C.H., Eyles, N., Gostin, V.A., 1998. Facies and allostratigraphy of high-latitude, glacially-influenced marine strata of the early Permian southern Sydney Basin, Australia. Sedimentology 45, 121–161.

Eyles, C.H., Mory, A.J., Eyles, N., 2003. Carboniferous-Permian facies and tectono-stratigraphic successions of the glacially influenced and rifted Carnarvon Basin, Western Australia. Sedimentary Geology 155, 63–86.

Eyles, N., 1990. Marine debris flows: Late Precambrian "tillites" of the Avalonian–Cadomian orogenic belt. Palaeogeogr. Palaeoclimatol. Palaeoecol. 79, 73–98.

Eyles, N., 1993. Earth's glacial record and its tectonic setting. Earth-Sci. Rev. 35, 1–248.

Eyles, N., 1996. Passive margin uplift around the North Atlantic region and its role in Northern Hemisphere late Cenozoic glaciation. Geology 24, 103–106.

Eyles, N., 1997. Passive margin uplift around the North Atlantic region and its role in Northern Hemisphere late Cenozoic glaciation. Reply to Comments. Geology 25, 282–283.

Eyles, N., Clark, B.M., 1985. Gravity induced soft sediment deformation structures in glaciomarine sequences of the Late Proterozoic Port Askaig Formation, Scotland. Sedimentology 32, 784–814.

Eyles, N., Eyles, C.H., 1989. Glacially-influenced deep-marine sedimentation of the Late Precambrian Gaskiers Formation, Newfoundland, Canada. Sedimentology 36, 601–620.

Eyles, N., Eyles, C.H., 1992. Glacial depositional systems. In: Walker, R.G., James, N.P. (Eds.), Facies Models: Response to Sea Level Change. Geological Association of Canada Special Publication, St. Johns, NF, pp. 73–100.

Eyles, N., Eyles, C.H., 1993. Glacial geologic confirmation of an intraplate boundary in the Parana Basin of Brazil. Geology 21, 459–462.

Eyles, N., Eyles, C.H., Miall, A.D., 1983. Lithofacies types and vertical profile models: an alternative approach to the description and environment interpretation of glacial diamict and diamictite sequences. Sedimentology 30, 393–410.

Eyles, N., Eyles, C.H., Apak, S.N., Carlsen, G.C., 2001a. Late Paleozoic tectono-stratigraphic evolution and petroleum potential of the northern Canning Basin (Barbwire Terrace), Western Australia. Am. Assoc. Pet. Geol. 85, 989–1006.

Eyles, N., Daniels, J., Osterman, L.E., Januszczak, N., 2001b. Ocean Drilling Program Leg 178 (Antarctic Peninsula): sedimentology of glacially influenced continental margin topsets and foresets. Marine Geology 178, 135–156.

Eyles, N., Mory, A.J., Backhouse, J., 2002. Carboniferous–Permian palynostratigraphy of west Australia marine rift basins: resolving tectonic and eustatic controls during Gondwanan glaciations. Palaeogeogr. Palaeoclimatol. Palaeoecol. 184, 305–331.

Fairchild, I.J., 1993. Balmy Shores and icy wastes: the paradox of carbonates associated with glacial deposits in Neoproterozoic times. Sediment. Rev. 1, 1–16.

Fairchild, I.J., Hambrey, M.J., 1995. Vendian basin evolution in East Greenland and NE Svalbard. Precambrian Res. 73, 217–233.

Fairchild, I.J., Bradby, L., Spiro, B., 1994. Reactive carbonate in glacial systems; a preliminary synthesis of its creation, dissolution and reincarnation. In: Deynoux, M.M., Miller, J.M.G., Domack, E.W., Eyles, N., Fairchild, I.J., Young, G.M. (Eds.), Earth's Glacial Record. Cambridge Univ. Press, New york, pp. 176–192.

Fedo, C.M., Cooper, J.D., 2001. Sedimentology and sequence stratigraphy of Neoproterozoic and Cambrian units across a craton-margin hinge zone, southeastern California, and implications for the early evolution of the Cordilleran margin. Sediment. Geol. 141–142, 501–522.

Finn, C.A., Anandakrishnan, S., Goodge, J., Panter, K., Siddoway, C., Wilson, T., 2003. Eos 84, 4.

Fischer, A.G., 1982. Long term climatic oscillations recorded in stratigraphy. Climate in Earth History, Studies in Geophysics. National Academy Press, Washington, DC, pp. 97–104.

Fischer, A.G., 1984. The two Phanerozoic supercycles. In: Berggren, W.A., Van Couvering, J.A. (Eds.), Catastrophes in Earth History; The New Uniformitarianism. Princeton Univ. Press, Princeton, NJ, pp. 129–150.

Fischer, A.G., 1986. Climatic rhythms recorded in strata. Annu. Rev. Earth Planet. Sci. 14, 351–376.

Fitzgerald, P.G., 1992. The Transantarcitc Mountains of southern Victoria Land: the application of apatite fission track analysis of rift shoulder uplift. Tectonics 11, 634–662.

Flint, R.F., 1957. Glacial Geology and the Pleistocene Epoch. Wiley, New York, 589 pp.

Flint, R.F., Sanders, J.E., Rodgers, J., 1960. Diamictite, a substitute term for symmictite. Geol. Soc. Am. Bull. 71, 1809–1810.

Gawthorpe, R.L., Leeder, M.R., 2000. Tectono-sedimentary evolution of active extensional basins. Basin Res. 12, 195–218.

Gehling, J.G., Narbonne, G.M., Jensen, S., Droser, M.L., 1999. Simultaneous appearance of Ediacaran trace fossils and bilateral body fossils; implications for animal evolution. Geol. Assoc. Can., Progr. Abstr. 31, 362.

Geikie, J., 1894. The Great Ice Age, 3rd ed. Spottiswoode and Co., London, 850 pp.

Gevers, T.W., 1931. An ancient tillite in South West Africa. Trans. Geol. Soc. S. Afr. 34, 1–17.

Ghibaudo, G., 1992. Subaqueous sediment gravity flow deposits; practical criteria for their field description and classification. Sedimentology 39, 423–454.

Gilbert, R., 1990. Evidence for the subglacial meltwater origin and late Quaternary lacustrine environment of Bateau Channel, eastern Lake Ontario. Can. J. Earth Sci. 27, 939–945.

Glover, B.W., Key, R.M., May, F., Clark, G.C., Phillips, E.R., Chacksfield, B.C., 1995. A Neoproterozoic multi-phase rift sequence; the Grampian and Appin groups of the southwestern Monodhliath Mountains of Scotland. J. Geol. Soc. (Lond.) 152, 391–406.

Golonka, J., Ford, D., 2000. Pangean (Late Carboniferous–Middle Jurassic) paleoenvironment and lithofacies. Palaeogeogr. Palaeoclimatol. Palaeoecol. 161, 1–34.

Goodge, J.W., Myrow, P., Williams, I.S., Bowring, S.A., 2002. Age and provenance of the Beardmore Group, Antarctica; constraints on Rodinia supercontinent breakup. J. Geol. 110, 393–406.

Grey, K., Corkeron, M., 1998. Late Neoproterozoic stromatolites in glacigenic successions of the Kimberley region, Western Australia: evidence for a younger Marinoan glaciation? Precambrian Res. 92, 65–87.

Grey, K., Apak, S.N., Eyles, C.H., Stevens, M.K., Carlsen, G.M., 1999. Neoproterozoic glacigene successions, western Officer Basin, Western Australia. Geol. Surv. Western Austr. Annu. Rev. 1998–1999, 74–80.

Grey, K., Walter, M.R., Calver, C.R., 2003. Neoproterozoic biotic diversification: Snowball Earth or aftermath of the Acraman impact? Geology 31, 459–462.

Griffin, B.J., Preiss, W.V., 1976. The significance and provenance of stromatolitic clasts in a probable late Precambrian diamictite in northwestern Tasmania. Pap. Proc. R. Soc. Tasman. 110, 111–120.

Grotzinger, J.P., Bowring, S.A., Saylor, B.Z., Kaufman, A.J., 1995. Biostratigraphic and geochronologic constraints on early animal evolution. Science 270, 598–604.

Guan, B., Wu, R., Hambrey, M.J., Geng, W., 1986. Glacial sediments and erosional pavements near the Cambrian–Precambrian boundary in western Henan Province, China. J. Geol. Soc. (Lond.) 143, 311–323.

Halacy Jr., D.S., 1978. Ice or Fire? Surviving Climatic Change. Fitzhenry and Whiteside, Toronto. 212 pp.

Halfar, J., Godinez Orta, L., Goodfriend, G.A., Mucciarone, D.A., Ingle, J.C., Holden, P., 2001. Holocene–late Pleistocene nontropical carbonate sediments and tectonic history of the western rift basin of the southern Gulf of California. Sediment. Geol. 144, 149–174.

Hall, K., 1983. Some quantitative observations of clast shapes from the Dwyka tillite of Natal, South Africa. Trans. Geol. Soc. S. Afr. 86, 155–159.

Hallam, A., Wignall, P.B., 1997. Mass Extinctions and Their Aftermath. Oxford Univ. Press, New York. 320 pp.

Halverson, G.P., Kaufman, A.J., Hoffman, P.F., Soffer, G., 1999. Stratigraphy and carbon isotopic record through the Neoproterozoic Rasthoff Formation cap carbonate, Otavi Group, Northwest Namibia. Abstr. Programs - Geol. Soc. Am. 31, 486.

Hambrey, M.J., 1982. Late Precambrian diamictites of northeastern Svalbard. Geol. Mag. 119, 527–551.

Hambrey, M.J., 1989. The Late Proterozoic sedimentary record of East Greenland: its place in understanding the evolution of the Caledonide Orogen. Caled. Geol. Scand., 257–262.

Hambrey, M.J., Harland, W.B. (Eds.), 1981. Earth's Pre-Pleistocene Glacial Record. Cambridge Univ. Press, Cambridge, New York, 1024 pp.

Hambrey, M.J., Spencer, A.M., 1987. Late Precambrian glaciation of central East Greenland. Medd. Gronl., Geosci. 19 (50 pp.).

Harland, W.B., 1964. Critical evidence for a great infra-Cambrian glaciation. Geol. Rundsch. 54, 45–61.

Harland, W.B., 1997. Svalbard. In: Harland, W.B., Anderson, L.M., Manasrah, D. (Eds.), The Geology of Svalbard. Geological Society of London Memoir, vol. 17. Blackwell, London, pp. 1–15.

Harland, W.B., Bidgood, D.E.T., 1959. Palaeomagnetism in some Norwegian Sparagmites and the Late pre-Cambrian ice age. Nature 184, 1860–1862.

Harland, W.B., Herod, K.N., 1975. Glaciations through time. In: Wright, A.E., Moseley, F. (Eds.), Ice Ages: Ancient and Modern. Seel House Press, Liverpool, pp. 189–216.

Harland, W.B., Herod, K.N., Krinsley, D.H., 1966. The definition and identification of tills and tillites. Earth Sci. Rev. 2, 225–256.

Hartz, E.H., Torsvik, T.H., 2002. Baltica upside down; a new plate tectonic model for Rodinia and the Iapetus Ocean. Geology 30, 255–258.

Hefferan, K.P., Karson, J.A., Saquaque, A., 1992. Proterozoic collisional basins in a Pan-African suture zone, Anti-Atlas Mountains, Morocco. Precambrian Res. 54, 295–319.

Hein, F.J., 1982. Depositional mechanisms for deep-sea coarse clastic sediments, Cap Enrage Formation, Quebec. Can. J. Earth Sci. 19, 267–287.

Herrington, P.M., Fairchild, I.J., 1989. Carbonate shelf and slope facies evolution prior to Vendian glaciation, central East Greenland. In: Gayer, R.A. (Ed.), The Caledonide Geology of Scandinavia. Graham and Trotman, London, pp. 263–273.

Higgins, A.K., Soper, M.P., Leslie, A.G., Rasmussen, J.A., Sonderholm, M., 2001. Neoproterozoic Hekla Sund Basin, Eastern North Greenland: a pre-Iapetan extensional sequence thrust across its rift shoulders during the Caledonian orogeny. J. Geol. Soc. 158, 487–500.

Hill, A.C., Walter, M.R., 2000. Mid-Neoproterozoic (~ 830–750 Ma) isotope stratigraphy of Australia and global correlation. Precambrian Res. 100, 181–211.

Hoffman, P., 1991. Did the breakout of Laurentia turn Gondwanaland inside-out? Science 252, 1409–1412.

Hoffman, P.F., Maloof, A.C., 2001. Tilting at Snowballs. http://www.eps.harvard.edu/people/faculty/hoffman/TAG.html.

Hoffman, P.F., Schrag, D.P., 1999. The Snowball Earth. http://eps.harvard.edu/people/faculty/hoffman/snowball_paper.html.

Hoffman, P.F., Schrag, D.P., 2000. Snowball Earth. Sci. Am. 282, 68–75.

Hoffman, P.F., Schrag, D.P., 2002. The Snowball Earth hypothesis: testing the limits of global change. Terra Nova 14, 129–155.

Hoffman, P.F., Hawkins, D.P., Isachsen, C.E., Bowring, S.A., 1996. Precise U–Pb zircon ages for early Damaran magmatism is the Summas Mountains and Welwitschia Inlier, northern Damara belt, Namibia. Commun. Geol. Surv. Namib. 11, 47–52.

Hoffman, P.F., Kaufman, A.J., Halverson, G.P., 1998a. Comings and goings of global glaciations on a Neoproterozoic carbonate platform in Namibia. GSA Today 8, 1–9.

Hoffman, P.F., Kaufman, A.J., Halverson, G.P., Schrag, D.P., 1998b. A Neoproterozoic Snowball Earth. Science 281, 1342–1346.

Hoffman, P.H., 2002. Carbonates bounding glacial deposits: evidence for Snowball Earth episodes and greenhouse aftermaths in the Neoproterozoic Otavi Group of northern Namibia. International Association of Sedimentologists Field Excursion Guidebook, July 1–7.

Hoffman, P.H., Halverson, G.P., Kaufman, A.J., 1999. Sea-level changes associated with Neoproterozoic "snowball" Earth events in the Otavi Group, Namibia. Abstr. Programs - Geol. Soc. Am. 31, 486.

Honda, S., Yoshida, M., Ootorii, S., Iwane, Y., 2000. The timescale of plume generation caused by continental aggregation. Earth Planet. Sci. Lett. 176, 31–43.

Hostetler, S., Clark, P.U., Bartlein, P.J., Mix, A.C., Pisias, N.G., 1999. Mechanisms for the global transmission and registration of North Atlantic Heinrich events. J. Geophys. Res. 104, 3947–3952.

Hyde, W.T., Crowley, T.J., Baum, S.K., Peltier, W.R., 2000. Neoproterozoic 'Snowball Earth' simulations with a coupled climate/ice-sheet model. Nature 405, 425–429.

Imbrie, J., Imbrie, K., 1979. Ice Ages: Solving the Mystery. MacMillan, New York, 224 pp.

Isaacson, P.E., Hladil, J., Shen, J., Kalvoda, J., Grader, J., 1999. Late Devonian (Famennian) glaciation in South America and marine offlap on other continents. Palaeclimatol. Abh. Geol. B.-A. (Germany) 54, 1–463.

Isley, A.E., 1995. Hydrothermal plumes and the delivery of iron to banded iron formations. J. Geol. 103, 169–185.

James, N.P., Kendall, A.C., 1992. Introduction to carbonate and evaporite facies models. In: Walker, R.G., James, N.P. (Eds.), Facies Models. Geological Association of Canada, St. Johns, NF, pp. 265–276.

James, N.P., Narbonne, G.M., Kyser, K.T., 2001. Late Neoproterozoic cap carbonates: Mackenzie Mountains, northwestern Canada: precipitation and global glacial meltdown. Can. J. Earth Sci. 38, 1229–1262.

Japsen, P., Chalmers, J.A., 2000. Neogene uplift and tectonics around the North Atlantic. Overview. Glob. Planet. Change 24, 165–173.

Jensen, P.A., Wolff-Pedersen, E., 1996. Glacial or non-glacial origin for the Bigganjargga tillite, Finnmark, Norway. Geol. Mag. 133, 137–145.

Johansson, M., Stow, D.A.V., 1995. A classification scheme for shale clasts in deep water sandstones. In: Hartley, A.J., Prosser, D.J. (Eds.), Characterization of Deep Marine Clastic Systems. Geological Society of London Special Publications, vol. 94. Geological Society of London, London, pp. 221–241.

Jones, B., Desrichers, A., 1992. Shallow platform carbonates. In: Walker, R.G., James, N.P. (Eds.), Facies Models; Response to Sea Level Change. Geological Association of Canada, St. Johns, NF, Canada, pp. 277–301.

Karlstrom, K.E., Harlan, S.S., Williams, M.L., McLelland, J., Geissman, J.W., Åhäll, K.-I., 1999. Refining Rodinia: geologic evidence for the Australia–Western U.S. connection in the Proterozoic. GSA Today 9, 1–7.

Kaufman, A.J., 1997. An ice age in the tropics. Nature 386, 227–228.

Kaufman, A.J., Knoll, A.H., 1995. Neoproterozoic variations in the C-isotopic composition of seawater: stratigraphic and biogeochemical implications. Precambrian Res. 73, 27–49.

Kennedy, M.J., 1996. Stratigraphy, sedimentology, and isotopic geochemistry of Australian Neoproterozoic postglacial cap dolostones: deglaciation, δ^{13}C excursions, and carbonate precipitation. J. Sediment. Res. 66, 1050–1064.

Kennedy, M.J., Runnegar, B., Prave, A.R., Hoffman, K.H., Arthur, M.A., 1998. Two or four Neoproterozoic glaciations? Geology 26, 1059–1063.

Kennedy, M.J., Christie-Blick, N., Prave, A.R., 2001a. Carbon isotopic composition of Neoproterozoic glacial carbonates as a test of paleoceanographic models for Snowball Earth phenomena. Geology 29, 1135–1138.

Kennedy, M.J., Christie-Blick, N., Sohl, L.E., 2001b. Are Proterozoic cap carbonates and isotopic excursions a record of gas hydrate destablization following Earth's coldest intervals? Geology 29, 443–446.

Kim, S.B., Chough, S.K., Chun, S.S., 1995. Bouldery deposits in the lowermost part of the Cretaceous Kyokpori Formation, SW Korea; cohensionless debris flows and debris falls on a steep-gradient delta slope. Sediment. Geol. 98, 97–119.

Kirschvink, J.L., 1992. Late Proterozoic low-latitude global glaciation: the Snowball Earth. In: Schopf, J.W., Klein, C. (Eds.), The Proterozoic Biosphere, A Multidisciplinary Study. Cambridge Univ. Press, Cambridge, pp. 51–52.

Knoll, A.H., 2000. Learning to tell Neoproterozoic time. Precambrian Res. 100, 3–20.

Knoll, A.H., Bambach, R.K., Canfield, D.E., Grotzinger, J.P., 1996. Comparative Earth history and late Permian mass extinction. Science 273, 452–457.

Kooi, H., Beaumont, C., 1994. Escarpment evolution on high-elevation rifted margins: insights derived from a surface processes model that combines diffusion, advection, and reaction. J. Geophys. Res. 99, 12191–12209.

Koster, E.H., Steel, R.J. (Eds.), 1984. Sedimentology of Gravels and Conglomerates. Canadian Society of Petroleum Geologists, Calgary. 441 pp.

Kröner, A., 1981. Late Precambrian diamictites of South Africa and Namibia. In: Hambrey, M.J., Harland, W.B. (Eds.), Earth's Pre-Pleistocene Glacial Record. Cambridge Univ. Press, Cambridge, pp. 167–177.

Kröner, A., Rankama, K., 1972. Late Precambrian glaciogenic sedimentary rocks in southern Africa: a compilation with definitions and correlations. Cape Town, Precambrian Res. Unit Bull. 11 (37 pp.).

Kröner, A., McWilliams, M.O., Germs, J.B., Reid, A.B., Schalk, K.E.L., 1980. Paleomagnetism of Late Precambrian to early Paleozoic mixtite-bearing formations in Namibia (South West Africa): the Nama Group and Blaubeker formation. Am. J. Sci. 280, 942–968.

Kuenen, P.H., Migliorini, C.I., 1950. Turbidity currents as a cause of graded bedding. J. Geol. 58, 91–127.

Kumpulainen, R., Nystuen, J.P., 1985. Late Proterozoic basin evolution and sedimentation in the westernmost part of Baltoscandia. In: Gee, D.G., Sturt, B.A. (Eds.), The Caledonide Orogen, Scandinavia and Related Areas. Wiley, London.

Laajoki, K., 2002. New evidence of glacial abrasion of the Late Proterozoic unconformity around Varangerfjorden, northern Norway. IAS Spec. Publ. 33, 405–436.

Labotka, T.C., Bergfeld, D., Nabelek, P.I., 2000. Two diamictites, two cap carbonates, two δ^{13}C excursions, two rifts: the Neoproterozoic Kingston Peak Formation, Death Valley, California: comment and reply. Geology 28, 191–192.

Lagoe, M.B., Eyles, C.H., Eyles, N., Hale, C., 1993. Dating the onset of Late Cenozoic glaciation in the North Pacific Ocean. Geol. Soc. Am. Bull. 105, 1542–1560.

Lamb, H.H., 1978. Climatic History and the Future. Princeton Univ. Press, Princeton, NY, 835 pp.

Lawson, D.E., 1979. A comparison of pebble orientations in ice and deposits of the Matanuska Glacier, Alaska. J. Geol. 87, 629–645.

Leather, J., Allen, P., Brasier, M.D., Cozzi, A., 2002. Neoproterozoic Snowball Earth under scrutiny: evidence from the Fiq glaciation of Oman. Geology 30, 891–894.

Ledesma, V.J., Johnson, M.E., 2001. Miocene–Pleistocene tectonosedimentary evolution of Bahia Concepcion region, Baja California Sur (Mexico). Sediment. Geol. 144, 83–96.

Leeming, D., Leeming, M., 1994. A Dictionary of Creation Myths. Oxford Univ. Press, New York, 330 pp.

LeGrand, H.E., 1988. Drifting Continents and Shifting Theories. Cambridge Univ. Press, New York. 313 pp.

LeMasurier, W.E., Landis, C.A., 1996. Mantle-plume activity recorded by low-relief erosion surfaces in West Antarctica and New Zealand. Geol. Soc. Amer. Bull. 108, 1450–1466.

Lemon, N.M., 1985. Physical modeling of sedimentation adjacent to diapirs and comparison with late Precambrian Oratunga breccia body in central Flinders Ranges, South Australia. AAPG Bull. 69, 1327–1338.

Lemon, N.M., Gostin, V.A., 1990. Glacigenic sediments of the Late Proterozoic Elatina Formation and equivalents, Adelaide Geosyncline, South Australia. Spec. Publ. - Geol. Soc. Aust. 16, 149–163.

Le Roex, H.D., 1941. A tillite in the Otavi mountains, S.W.A. Geol. Soc. S. Afr. Trans. 44, 207–218.

Li, Z.X., Powell, C.M., 2001. An outline of the palaeogeographic evolution of the Australasian region since the beginning of the Neoproterozoic. Earth Sci. Rev. 53, 237–277.

Li, Z.X., Zhang, L., Powell, M., 1996. Positions of the East Asian cratons in the Neoproterozoic supercontinent Rodinia. Aust. J. Earth Sci. 43, 593–604.

Li, Z.X., Li, Z.H., Kinny, P.D., Wang, J., 1999. The breakup of Rodinia: did it start with a mantle plume beneath South China? Earth Planet. Sci. Lett. 173, 171–181.

Licciardi, J.M., Teller, J.T., Clark, P.U., 1999. Freshwater routing by the Laurentide Ice Sheet during the last deglaciation. In: Clark, P.U., Webb, R.S., Keigwin, L.D. (Eds.), Mechanisms of Global Climate Change at Millennial Time Scales. American Geophysical Union, Washington, DC.

Lindsay, J.F., 1989. Depositional controls on glacial facies associations in a basinal setting, Late Proterozoic, Amadeus Basin, Central Australia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 73, 205–232.

Lindsay, J.F., Brasier, M.D., 2002. Did global tectonics drive early biosphere evolution? Carbon isotope record from 2.6 to 1.9 Ga carbonates of Western Australian basins. Precambrian Res. 114, 1–34.

Lindsay, J.F., Korsch, R.J., Wilford, J.R., 1987. Timing the breakup of a Proterozoic supercontinent: evidence from Australian intracratonic basins. Geology 15, 1061–1064.

Lindsay, J.F., Brasier, M.D., Sheilds, G., Khomentovsky, V.V., Bat-Ireedui, Y.A., 1996. Glacial facies associations in a Neoproterozoic back-arc setting, Zavkhan Basin, western Mongolia. Geol. Mag. 133, 391–402.

Link, P.K., Gostin, V.A., 1981. Facies and paleogeography of Sturtian glacial strata (late Precambrian), South Australia. Am. J. Sci. 281, 353–374.

Link, P.K., Miller, J.M.G., Christie-Blick, N., 1993. Glacial-marine facies in a continental rift environment: Neoproterozoic rocks of the western United States Cordillera. In: Deynoux, M., Miller, J.M.G., Domack, E.W., Eyles, N., Fairchild, I.J., Young, G.M. (Eds.), Earth's Glacial Record. Cambridge Univ. Press, Cambridge, pp. 29–46.

Lirer, L., Vinci, A., Alberico, I., Gifuni, T., Bellucci, F., Petrosino, P., Tinterri, R., 2001. Occurrence of inter-eruption debris flow and hyperconcentrated flood-flow deposits on Vesuvio Volcano, Italy. Sediment. Geol. 139, 151–167.

Lowe, D.R., Guy, M., 2000. Slurry-flow deposits in the Britannia Formation (Lower Cretaceous), North Sea: a new perspective on the turbidity current and debris flow problem. Sedimentology 47, 31–70.

Lu, S., Zhenjia, G., 1991. A comparative study on the characteristics of the debris flow and glacial deposits of Late Proterozoic in the Aksu area of Xinjiang. Bulletin of the 562 Comprehensive Geological Brigade, Chinese Academy of Geological Sciences 9, 1–16.

MacNaughton, R.B., Narbonne, G.M., Dalrymple, R.W., 2000. Neoproterozoic slope deposits, Mackenzie Mountains, northwestern Canada: implications for passive-margin development and Ediacaran faunal ecology. Can. J. Earth Sci. 37, 997–1020.

Malcuit, R.J., Winters, R.R., 1985. Computer simulation model for early and post-capture phase if lunar orbital evolution; implications for thermal history of Earth and Moon. Abstr. Programs Geol. Soc. Am. 17, 651.

Martin, H., 1965. Observations on the problem of late Precambrian glacial deposits in South-West Africa. Geol. Rundsch. 54, 115–127.

Martin, H., Porada, H., Walliser, O.H., 1985. Mixtite deposits of the Damara sequence, Namibia: problem of interpretation. Palaeogeogr. Palaeoclimatol. Palaeoecol. 51, 159–196.

Martin, M.W., Grazhdankin, D.V., Bowring, S.A., Evans, D.A.D., Fedonkin, M.A., Kirschvink, J.L., 2000. Age of Neoproterozoic bilaterian body and trace fossils, White Sea, Russia; implications for metazoan evolution. Science 288, 841–845.

Martins-Neto, M.A., 1998. Mantle plume, rifting and the early Neoproterozoic glaciation in the Sao Francisco craton and Aracuai fold belt, southeastern Brazil. International Conference in Basement Tectonics Program and Abstracts, vol. 14, pp. 32–34.

Martins-Neto, M.A., Pedrosa-Soares, A.C., Lima, S.A.A., 2001. Tectono-sedimentary evolution of sedimentary basins from late Paleoproterozoic to late Neoproterozoic in the Sao Francisco craton and Aracuai fold belt, eastern Brazil. Sediment. Geol. 141–142, 343–370.

Masson, D.G., Canals, M., Alonso, B., Urgeles, R., Huhnerbach, V., 1998. The Canary debris flow; source area morphology and failure mechanisms. Sedimentology 45, 411–432.

Mawson, D., 1949. The Elatina glaciation: a third recurrence of glaciation evidenced in the Adelaide system. Trans. Geol. Soc. S. Afr. 73, 117–121.

Mawson, M., 1958. Letter to Sir Raymond Priestley. In: Jacka, F., Jacka, E. (Eds.), Mawson's Antarctic Diaries. Unwin, Sydney, 1988, 414 pp.

McGinnis, J.P., Driscoll, N.W., Karner, G.D., Brumbaugh, W.D., Cameron, N., 1993. Flexural response of passive margins to deep-sea erosion slope retreat: implications for relative sea-level change. Geology 21, 893–896.

McKenzie, D.P., Parker, R.L., 1967. The north Pacific: an example of tectonics on a sphere. Nature 216, 1276–1280.

McManus, J.F., Oppo, D.W., Cullen, J.L., 1999. A 0.5-million-year record of millennial-scale climate variability in the North Atlantic. Science 283, 971–975.

McMechan, M.E., 2000. Vreeland diamictites: Neoproterozoic glaciogenic slope deposits, Rocky Mountains, Northeast British Columbia. Bull. Can. Pet. Geol. 48, 246–261.

McWilliams, M.O., Kröner, A., 1981. Paleomagnetism and Tectonic evolution of the Pan-African Damara belt, Southern Africa. J. Geophys. Res. 86, 5147–5162.

Meert, J.G., van der Voo, R., 1994. The Neoproterozoic (1000–540 Ma) glacial intervals: no more Snowball Earth? Earth Planet. Sci. Lett. 123, 1–13.

Mendelson, C., Schopf, J.W., 1992. Proterozoic and early Cambrian acritarchs. In: Schopf, J.W., Klein, C. (Eds.), The Proterozoic Biosphere. Cambridge Univ. Press, Cambridge, pp. 219–231.

Merritts, D., Ellis, M., 1994. Introduction to special section on tectonics and topography. J. Geophys. Res. 99, 12135–12141.

Miall, A.D., 1985. Sedimentation on an early Proterozoic continental margin under glacial influence: the Gowganda Formation (Huronian), Elliot Lake area, Ontario, Canada. Sedimentology 32, 763–788.

Miall, A.D., 1991. Stratigraphic sequences and their chronostratigraphic correlation. J. Sediment. Petrol. 61, 497–505.

Miall, A.D., 1995. Whither stratigraphy? Sediment. Geol. 100, 5–20.

Miall, A.D., 1997. The Geology of Stratigraphic Sequences. Springer-Verlag, Berlin, 433 pp.

Miller, J., 1994. The Neoproterozoic Konnarock Foramtion, southwesten Virginia, USA: glaciolacustrine facies in a continental rift. In: Deynoux, M.M., Miller, J.M.G., Domack, E.W., Eyles, N., Fairchild, I.J., Young, G.M. (Eds.), Earth's Glacial Record. Cambridge Univ. Press, Cambridge, New York, pp. 47–59.

Monastersky, R., 1998. Popsicle planet: the king of all ice ages may have spurred animal evolution. Sci. News 54, 137–139.

Moncrieff, A.C.M., 1990. Late Precambrian tillites in East Greenland; a link between tectonic uplift and glaciation. Int. Sediment. Congr. 13, 364–365.

Moncrieff, A.C.M., Hambrey, M.J., 1988. Late Precambrian glacially-related grooved and striated surfaces in the Tillite Group of central East Greenland. Palaeogeogr. Palaeoclimatol. Palaeoecol. 65, 183–200.

Moore, D.G., Currray, J.R., Einsele, G., 1982. Salado–Vinorama submarine slide and turbidity current off the southeast tip of Baja California. Initial Reports of the Deep Sea Drilling Project, vol. 64, pp. 1071–1082.

Moores, E.M., 1991. Southwest U.S.–East Antarctic (SWEAT) connection: a hypothesis. Geology 19, 425–428.

Morris, W.A., 1977. Paleolatitude of glaciogenic upper Precambrian Rapitan Group and the use of tillites as chronostratigraphic marker horizons. Geology 5, 85–88.

Moussine-Pouchkine, A., Bertrand-Sarfati, J., 1997. Tectonosedimentary subdivisions in the Neoproterozoic to Early Cambrian cover of the Taoudenni Basin (Algeria–Mauritania–Mali). J. Afr. Earth Sci. 24, 425–443.

Mulder, T., Alexander, J., 2001. The physical character of subaqueous sedimentary density flows and their deposits. Sedimentology 48, 269–299.

Mutti, E., 1992. Turbidite Sandstones. AGIP, Italy (ITA), 275 pp.

Nance, R.D., Worsley, T.R., Moody, J.G., 1986. Post-Archean biogeochemical cycles and long term episodicity in tectonic processes. Geology 14, 514–518.

Narbonne, G.M., 1998. The Ediacara biota: a terminal Neoproterozoic experiment in the evolution of life. GSA Today 8, 1–6.

Narbonne, G.M., Aitken, J.D., 1995. Neoproterozoic of the Mackenzie Mountains, northwestern Canada. Precambrian Res. 73, 101–121.

Narbonne, G.M., Gehling, J.M., 2003. Life after snowball: the oldest complex Ediacaran fossils. Geology 31, 27–30.

Narbonne, G.M., Hoffman, H.J., 1987. Ediacaran biota of the Wernecke Mountains, Yukon, Canada. Palaeontology 30, 647–676.

Narbonne, G.M., Kaufman, A.J., Knoll, A.H., 1994. Integrated chemostratigraphy and biostratigraphy of the Windermere Supergroup, northwestern Canada: implications for Neoproterozoic correlations and the early evolution of animals. Geol. Soc. Am. Bull. 106, 1281–1292.

Nelson, D.R., 2001. An assessment of the determination of depositional ages for Precambrian clastic sedimentary rocks by U–Pb dating of detrital zircons. Sediment. Geol. 141–142, 37–60.

Nemec, W., Steel, R.J., 1984. Alluvial and coastal conglomerates: their significant features and some comments on gravelly mass flow deposits. In: Koster, E.H., Steel, R.J. (Eds.), Sedimentology of Gravels and Conglomerates. Canadian Society of Petroleum Geologists, Calgary, pp. 1–31.

Nemec, W., Steel, R.J., Porebski, S.J., Spinnangr, A., 1984. Domba Conglomerate, Devonian, Norway: process and lateral variability in a mass flow-dominated lacustrine fan-delta. In: Koster, E.H., Steel, R.J. (Eds.), Sedimentology of Gravels and Conglomerates. Canadian Society of Petroleum Geologists, Calgary, pp. 295–330.

Nicoaill, C.M., van der Pluijm, B., Torsvik, T., 2001. Gathering recognizes contributions of former section president. Eos. Trans. AGU 82, 557.

North, F.J., 1943. Centenary of the Glacial Theory. Proc. Geol. Assoc. LIV, 1–28.

Nystuen, J.P., 1985. Facies and preservation of glaciogenic sequences from the Varanger ice age in Scandanavia and other parts of the North Atlantic region. Palaeogeogr. Palaeoclimatol. Palaeoecol. 51, 209–229.

Oberbeck, V.R., Hoerz, F., Bunvh, T., 1993. Impacts, tillites and the breakup of Gondwana. J. Geol. 101, 1–19.

Ojakangas, R.W., 1985. Early Proterozoic glaciation: the dropstone unit-diamictite association. Geol. Surv. Finl. Bull. 331, 51–72.

Ojakangas, R.W., 1988. Glaciation: an uncommon "mega-event" as a key to intracontinental and intercontinental correlation of Early Proterozoic basin fill, North American and Baltic cratons. In: Kleinspehn, K.L., Paola, C. (Eds.), New Perspectives in Basin Analysis. Springer, New York, pp. 431–444.

Ojakangas, R.W., Morey, G.B., Southwick, D.L., 2001. Paleoproterozoic basin development and sedimentation in the Lake Superior region, North America. Sediment. Geol. 141–142, 319–341.

Park, J.K., 1997. Paleomagnetic evidence for low-latitude glaciation during deposition of the Neoproterozoic Rapitan Group, Mackenzie Mountains, N.W.T., Canada. Can. J. Earth Sci. 34, 34–49.

Parmenter, A.G., Lee, C.B., Coniglio, M., 2002. "Sudbury Breccia" at Whitefish Falls, Ontario: evidence of an impact origin. Can. J. Earth Sci. 39, 971–982.

Paul, M.A., Eyles, N., 1990. Constraints on the preservation of diamict facies (melt-out tills) at the margins of stagnant glaciers. Quat. Sci. Rev. 9, 51–69.

Pauly, K.A., 1957. The Cause of the Great Ice Ages. Privately printed, 60 pp.

Pettijohn, F., 1957. Sedimentary Rocks. Harper, New York. 718 pp.

Pettijohn, F., 1984. Diary of an Unrepentant Field Geologist. University of Chicago Press, Chicago, 260 pp.

Piper, D.J.W., 1970. A Silurian deep sea fan deposit in western Ireland and its bearing on the nature of turbidity currents. J. Geol. 78, 509–522.

Pirajno, F., 2000. Ore deposits and mantle plumes. Kluwer, Boston, 556 pp.

Plink-Bjorklund, P., Ronnert, L., 1999. Depositional processes and internal architecture of Late Weichselian ice-margin submarine fan and delta settings, Swedish west coast. Sedimentology 46, 215–234.

Porada, H., Wittig, R., 1983. Turbidites in the Damara Orogen. In: Martin, H., Eder, F.W. (Eds.), Intracontinental Fold Belts, Case Studies in the Variscan Belt of Europe and the Damara Belt in Namibia. Springer-Verlag, Berlin, pp. 543–576.

Postma, G., 1984. Mass-flow conglomerates in a submarine canyon: Abrioja Fan-Delta, Pliocene, southeast Spain. In: Koster, E.H., Steel, R.J. (Eds.), Sedimentology of Gravels and Conglomerates. Canadian Society of Petroleum Geologists, Calgary, pp. 237–258.

Postma, G., Nemec, W., Kleinspehn, K.L., 1988. Large floating clasts in turbidites: a mechanism for their emplacement. Sediment. Geol. 58, 47–61.

Powell, R.D., 1981. A model for sedimentation by tidewater glaciers. Ann. Glaciol. 2, 129–134.

Powell, C.M., Pisarevsky, S.A., 2002. Late Neoproterozoic assembly of East Gondwana. Geology 30, 3–6.

Powell, C.M., Veevers, J.J., 1987. Namurian uplift in Australia and South America triggered the main Gondwanan glaciation. Nature 326, 177–179.

Powell, C.M., Preiss, W.V., Gatehouse, C.G., Krapez, B., Li, Z.X., 1994. South Australian record of a Rodinian epicontinental basin and its mid-Neoproterozoic breakup (approximately 700 Ma) to form the palaeo-Pacific Ocean. Tectonophysics 237, 113–140.

Prave, A.R., 1996. Tale of three cratons: tectonostratigraphic anatomy of the Damara orogen in northwestern Namibia and the assembly of Gondwana. Geology 24, 1115–1118.

Prave, A.R., 1999. Two diamictites, two cap carbonates, two $\delta^{13}C$ excursions, two rifts: the Neoproterozoic Kingston Peak Formation, Death Valley, California. Geology 27, 339–342.

Prave, A.R., Hoffmann, K.H., 1995. Unequivocal evidence for two Neoproterozoic glaciations in the Damara sequence of Namibia. Abstr. Programs - Geol. Soc. Am. 27, 380.

Preiss, W.V., 1987. The Adelaide Geosyncline: Late Proterozoic stratigraphy, palaeontology and tectonics. Geol. Surv. South Aust. Bull. 53, 438 pp.

Preiss, W.V., 1990. A stratigraphic and tectonic overview of the Adelaide Geosyncline, South Australia. In: Jago, J.B., Moore, P.S. (Eds.), The Evolution of a Late Precambrian–Early Palaeozoic Rift Complex; The Adelaide Geosyncline. Spec. Publ. Geol. Soc. Aust., vol. 16, pp. 1–33.

Preiss, W.V., 1999. Parachilna, South Australia. 1:230,000 Geological Series Sheet SH54-13. Explanatory Notes, Primary Industries and Resources, South Australia, 52 pp.

Proust, J.N., Deynoux, M., 1994. Marine to non-marine sequence architecture of an intracratonic glacially related basin. Late Neoproterozoic of the West African platform in western Mali. In: Deynoux, M.M., Miller, J.M.G., Domack, E.W., Eyles, N., Fairchild, I.J., Young, G.M. (Eds.), Earth's Glacial Record. Cambridge Univ. Press, Cambridge, pp. 121–145.

Proust, J.N., Deynoux, M., Guillocheau, F., 1990. Dynamic anatomy of a basin fringe: Late Proterozoic glacial Bakoye Group, western Mali, West Africa. C.R. Acad. Sci. Paris 310, 255–261.

Prueher, L.M., Rea, D.K., 2001. Volcanic triggering of late Pliocene glaciation: evidence from the flux of volcanic glass and ice-rafted debris to the North Pacific Ocean. Palaeogeogr. Palaeoclimatol. Palaeoecol. 173, 215–230.

Rampino, M.R., 1994. Tillites, diamictites and ballistic ejecta of large impacts. J. Geol. 101, 439–456.

Rankin, D.W., 1993. The volcanogenic Mount Rogers Formation and the overlying glaciogenic Konnarock Formation—two Late Proterozoic units in southwestern Virginia. U.S. Geol. Surv. Bull. 2029, 26 pp.

Ravnas, R., Steel, R.J., 1998. Architecture of marine rift–basin successions. Am. Assoc. Pet. Geol. Bull. 82, 110–146.

Raymo, M.E., Ruddiman, W.F., 1992. Tectonic forcing of Late Cenozoic climate. Nature 359, 117–122.

Reinke-Kunze, C., 1994. Alfred Wegener: Polarforscher und Entdecker der Kontinentaldrift. Birkhäuser Verlag, Boston. 188 pp.

Retallack, G.J., 1994. Were the Ediacaran fossils lichens? Palaeobiology 20, 523–544.

Reusch, H., 1891. Skruinsmerker og moraenegrus eftervist I finmarken fra en period megetaeldre end "istiden". Nor. Geol. Unders. 1, 97–100.

Roberts, J.D., 1971. Later Precambrian glaciation: and anti-greenhouse effect? Nature 234, 216–217.

Roberts, J.D., 1976. Late Precambrian dolomites, Vendian glaciation and sychroneity of Vendian glaciations. J. Geol. 84, 47–63.

Roberts, J.D., 1977. Discussion of Late Precambrian dolomites, Vendian glaciation, and synchroneity of Vendian glaciations: a reply. J. Geol. 85, 251–252.

Rohrbach, K., 1993. Alfred Wegener. Erforscher der Wandernden Kontinente. Verlag Freies Geistesleben, Stuttgart, 255 pp.

Ross, G.M., Bloch, J.D., Krouse, H.R., 1995. Neoproterozoic strata of the southern Canadian Cordillera and the isotopic evolution of seawater sulfate. Precambrian Res. 73, 71–99.

Ruddiman, W.F., Kutzbach, J.E., 1989. Forcing of Late Cenozoic northern hemisphere climate by plateau uplift in Southern Asia and the American West. J. Geophys. Res. 94, 18409–18427.

Runnegar, B., 2000. Loophole for Snowball Earth. Nature 405, 403–404.

Sayles, R.W., 1914. The Squantum tillite. Mem. Mus. Comp. Zool. Harv. Coll. X., pp. 141–175.

Sayles, R.W., 1919. Seasonal deposition in aqueo-glacial sediments. Mem. Mus. Comp. Zool. Harv. Coll. XLVII, 67 pp.

Saylor, B.Z., Kaufman, A.J., Grotzinger, J.P., Urban, F., 1998. A composite reference section for terminal Proterozoic strata of southern Namibia. J. Sediment. Res. 68, 1223–1235.

Schermerhorn, L.J.G., 1966. Terminology of mixed coarse-fine sediments. J. Sediment. Petrol. 36, 831–836.

Schermerhorn, L.J.G., 1974a. Late Precambrian mixtites: glacial and/or nonglacial? Am. J. Sci. 274, 673–824.

Schermerhorn, L.J.G., 1974b. No evidence for glacial origin of Late Precambrian tilloids in Angola. Nature 252, 114–116.

Schermerhorn, L.J.G., 1975. Tectonic framework of Late Precambrian supposed glacials. In: Wright, A.E., Moseley, F. (Eds.), Ice Ages: Ancient and Modern. Geol. J. Spec. Publ., pp. 241–274.

Schermerhorn, L.J.G., 1977. Late Precambrian dolomites, Vendian glaciation and synchroneity of Vendian glaciations: a discussion. J. Geol. 85, 247–250.

Schermerhorn, L.J.G., 1981. Late Precambrian tilloids of Northwest Angola. In: Hambrey, M.J., Harland, W.B. (Eds.), Earth's Pre-Pleistocene Glacial Record. Cambridge Univ. Press, Cambridge, pp. 158–161.

Schermerhorn, L.J.G., 1983. Late Proterozoic glaciation in the light of CO_2 depletion in the atmosphere. Mem. Geol. Soc. Am. 161, 309–315.

Schmidt, P.W., Williams, G.E., 1995. The Neoproterozoic climactic paradox: equatorial palaeolatitude for Marinoan glaciation near sea level in South Australia. Earth Planet. Sci. Lett. 134, 107–124.

Schmidt, P.W., Embleton, B.J.J., Williams, G.E., 1993. Early timing of remanence in haematite of the Neoproterozoic Elatina Formation, Adelaide Geosyncline: confirmation of the low palaeolatitude of Neoproterozoic glaciation. Explor. Geophys. 24, 239–242.

Schrag, D.P., Hoffman, P.F., 2001. Life, geology and Snowball Earth—correspondence to Hyde et al. 2000. Nature 409, 306.

Sellers, W.D., 1969. A global climatic model based on the energy balance of the Earth–atmosphere system. J. Appl. Meteorol. 8, 392–400.

Sellers, W.D., 1990. The genesis of energy balance modelling and the cool sun paradox. Palaeogeogr. Palaeoclimatol. Palaeoecol. 82, 217–224.

Sengör, A.M.C., 1995. Sedimentation and Tectonics of Fossil Rifts. In: Busby, C.J., Ingersoll, R.V. (Eds.), Tectonics of Sedimentary Basins. Blackwell Science, Cambrigde, MA, pp. 53–117.

Sheldon, R.P., 1984. Ice ring origin of the Earth's atmosphere and hydrosphere and Late Proterozoic–Cambrian phosphogenesis-Rao, G.V., Dasgupta, S.P., Pant, A., Choudhiri, R. (Eds.), Phosphorite. Geol. Surv. Spec. Publ. Ser., India, vol. 17, pp. 17–21.

Shields, G.A., 1999. Post-glacial carbonates of the Adrar region, Mauritania and the Snowball Earth hypothesis. Abstr. Programs - Geol. Soc. Am. 31, 487.

Shields, G.A., Brasier, M.D., Stille, P., Dorjnamjaa, D., 2002. Factors contributing to high 13C values in Cryogenian limestones of western Mongolia. Earth Planet. Sci. Lett. 196, 99–111.

Simonson, B.M., 1985. Sedimentological constraints on the origins of Precambrian iron-formations. Geol. Soc. Am. Bull. 96, 244–252.

Smith, D.A.M., 1965. The geology of the area around the Khan and Swakop Rivers in South West Africa. Geol. Surv. South West Afr. Ser. Mem. 3, 24–27.

Smith, M.P., Robertson, S., Rollin, K.E., 1999. Rift basin architecture and stratigraphical implications for basement-cover relationships in the Neoproterozoic Grampian Group of the Scottish Caledonides. J. Geol. Soc. (Lond.) 156, 1163–1173.

Socci, A.D., Smith, G.W., 1987. Evolution of the Boston Basin: a sedimentological perspective. In: Beaumont, C., Tankard, A.J. (Eds.), Basin Forming Mechanisms. Mem. Can. Soc. Pet. Geol. 12, 87–99.

Sochava, A.V., Podkovyrov, V.N., 1995. The compositional evolution of Meso- and Neopreterozoic carbonate rocks. Precambrian Res. 73, 283–289.

Sohl, L.E., Christie-Blick, N., Kent, D.V., 1999. Paleomagnetic polarity reversals in the Marinoan (ca. 600 Ma) glacial deposits of Australia: implications for the duration of low-latitude glaciation in Neoproterozoic time. Geol. Soc. Am. Bull. 111, 1120–1139.

Sonderholm, M., Jepsen, H.J., 1991. Proterozoic basins of North Greenland. Bull. Gronl. Geol. Unders. 160, 46–69.

Soper, N.J., England, R.W., 1995. Vendian and Riphean rifting in NW Scotland. J. Geol. Soc. (Lond.) 152, 11–14.

Spencer, A.M., 1971. Late Precambrian glaciation in Scotland. Mem. Geol. Soc. Lond. 6, 1–48.

Stanton, W.I., Schermerhorn, L.J.G., 1976. Late Precambrian glacial climate and the Earth's obliquity—a discussion. Geol. Mag. 114, 57–64.

Storey, B.C., 1995. The role of mantle plumes on continental breakup: case histories from Gondwanaland. Nature 377, 301–308.

Stump, E., Miller, J.M.G., Korsch, R.J., Edgerton, D.G., 1988. Diamictite from Nimrod Glacier area, Antarctica: possible Proterozoic glaciation on the seventh continent. Geology 16, 225–228.

Summa, C.L., Grotzinger, J.P., Southard, J.B., 1993. Stratigraphic evidence for Neoproterozoic continental breakup along the western Cordilleran margin. Abstr. Programs - Geol. Soc. Am. 25, 171.

Surlyk, F., 1991. Tectonostratigraphy of North Greenland. Bull. Gronl. Geol. Unders. 160, 25–47.

Tarling, D.H., 1974. A paleomagnetic study of Eocambrian tillites in Scotland. J. Geol. Soc. (Lond.) 130, 163–177.

Thompson, M.D., Bowring, S.A., 2000. Age of the Squantum "tillite", Boston Bay Group, Massachusetts: U–Pb zircon constraints on terminal Neoproterozoic glaciation. Am. J. Sci. 300, 630–655.

Tojo, B., et al., 1999. Cyclicities in Earth-warming episode recorded in the Rasthof cap carbonate overlying the Neoproterozoic Chuos diamictite in Namibia. Abstr. Programs - Geol. Soc. Am. 31, 486–487.

Torsvik, T.H., Meert, J.G., 1995. Baltica and Laurentia: two continents, two supercontinents and a whole lot of tectonics. Abstr. Programs - Geol. Soc. Am. 27, 93.

Torsvik, T.H., Smethurst, M.A., Meert, J.G., Van der Voo, R., McKerrow, W.S., Brasier, M.D., Stuart, B.A., Walderhaug, H.J., 1996. Continental break-up and collision in the Neoproterozoic and Palaeozoic—a tale of Baltica and Laurentia. Earth-Sci. Rev. 40, 229–258.

Trompette, R., 1994. Geology of Western Gondwana (2000–500 Ma): Pan-African–Brasiliano Aggregation of South America and Africa. A.A. Balkema, Rotterdam, 350 pp.

Turner, J.V., 1982. Kinetic fractionation of carbon-13 during calcium carbonate precipitation. Geochim. Cosmochim. Acta 40, 1183–1191.

Unrug, R., 1997. Rodinia to Gondwana: the geodynamic map of Gondwana supercontinent assembly. GSA Today 7, 1–6.

Vagnes, E., Amundsen, H.E.F., 1993. Late Cenozoic uplift and volcanism on Spitsbergen: caused by mantle convection? Geology 21, 251–254.

Vail, P.R., 1992. The evolution of seismic stratigraphy and the global sea level curve. In: Dott, R.H.J. (Ed.), Eustacy: The Historical Ups and Downs of a Major Geological Concept. Mem. Geol. Soc. Am. 180, 83–91.

Van Wagoner, J.C., Posamentier, H.W., Mitchum Jr., R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., Hardenbol, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. Sea-Level Changes; An Integrated Approach. Spec. Publ. - Soc. Econ. Paleontol. Mineral. 42, 39–45.

Veevers, J.J., 1990. Tectonic climatic supercycle in the billion-year plate tectonic eon: Permian Pangean icehouse alternates with Cretaceous dispersed continent s greenhouse. Sediment. Geol. 68, 1–16.

Veevers, J.J., McElhinny, M.W., 1976. The separation of Australia from other continents. Earth Sci. Rev. 12, 139–159.

Vidal, G., Moczydlowska, M., 1995. The Neoproterozoic of Baltica: stratigraphy, palaeobiology and general geological evolution. Precambrian Res. 73, 197–216.

Visser, J.N.J., 1987. Influence of topography on the Permo-Carboniferous glaciation in the Karoo Basin and adjoining areas, southern Africa. In: McKenzie, G.D. (Ed.), Gondwana 6. Geophys. Monogr., vol. 41. American Geophysical Union, pp. 123–129.

Visser, J.N.J., 1991. The paleoclimatic setting of the Late Proterozoic marine ice sheet in the Karoo Basin of southern Africa. In: Anderson, J.B., Ashley, G.M. (Eds.), Glacial Marine Sedimentation: Paleoclimatic Significance. Spec. Pap. - Geol. Soc. Am. 261, 181–190.

Visser, J.N.J., 1997. Deglaciation sequences in the Permo-Carboniferous Karoo and Kalahari basins of Southern Africa: a tool in the analysis of cyclic glaciomarine basin fills. Sedimentology 44, 507–521.

Visser, J.N.J., Loock, J.C., 1988. Sedimentary facies of the Dwyka Formation association with the Nooitgedacht glacial pavements, Barkly West District. S. Afr. J. Geol. 91, 38–48.

Visser, J.N.J., Praekelt, H.E., 1996. Subduction, mega-shear systems and late Palaeozoic basin development in the African segment of Gondwana. Geol. Rundsch. 85, 632–646.

Walter, M.R., Veevers, J.J., Calver, C.R., Grey, K., 1995. Neoproterozoic stratigraphy of the Centralian Superbasin, Australia. Precambrian Res. 73, 173–195.

Wang, Y., Lu, S., Gao, Z., Lin, W., Ma, G., 1981. Sinian tillites in China. In: Hambrey, M.J., Harland, W.B. (Eds.), Earth's Pre-Pleistocene Glacial Record. Cambridge Univ. Press, Cambridge, pp. 386–401.

Watanabe, Y., 2001. Oceanic anoxia at the Precambrian–Cambrian boundary. Geology 29, 995–998.

Waythomas, C.F., Wallace, K.L., 2002. Flank collapse at Mt. Wrangell, Alaska recorded by volcanic mass flow deposits in the Copper River lowland. Can. J. Earth Sci. 39, 1257–1279.

Webb, B.P., 1960. Diapiric structures in the Flinders Ranges, South Australia. Aust. J. Sci. 22, 390–391.

Wegener, A., 1912. The origin of continents. Geol. Rundsch. 3, 276–292.

Wegener, A.L., 1924. The Origin of Continents and Oceans. Trans. J.G.A.Skerl of 3rd German ed. Methuen & Co., London.

Wegener, A.L., 1928. Two notes concerning my theory of continental drift. In: van der Gracht, van Waterschoot, W.A.J.M. (Eds.), Theory of Continental Drift: A Symposium. American Association of Petroleum Geologists, Tulsa, pp. 97–103.

Wehr, F., 1986. A proglacial origin for the Upper Proterozoic Rockfish conglomerate, Central Virginia, USA. Precambrian Res. 34, 157–174.

Weill, A.B., Van der Voo, R., MacNiocaill, C., Meert, J.G., 1998. The Proterozoic supercontinent Rodinia: paleomagnetically derived reconstructions for 1100 to 800 Ma. Earth Planet. Sci. Lett. 154, 13–24.

Williams, G.E., 1975. Late Precambrian glacial climate and the Earth's obliquity. Geol. Mag. 112, 441–465.

Williams, G.E., 1986. Precambrian permafrost horizons as indicators of palaeoclimate. Precambrian Res. 32, 233–242.

Williams, G.E., 1988. Cyclicity in the Late Precambriam Elatina formation, South Australia, solar or tidal signature? Clim. Change 13, 117–128.

Williams, G.E., 1989a. Late Precambrian tidal rhythmites in South Australia and the history of the Earth's rotation. J. Geol. Soc. (Lond.) 146, 97–111.

Williams, G.E., 1989b. Precambrian tidal sedimentary cycles and Earth's paleorotation. Eos. Trans. AGU 70, 33, 40–41.

Williams, G.E., 1993. History of Earth's obliquity. Earth Sci. Rev. 112, 1–45.

Williams, G.E., 1994. The enigmatic Late Proterozoic glacial climate: an Australian perspective. In: Deynoux, M.M., Miller, J.M.G., Domack, E.W., Eyles, N., Fairchild, I.J., Young, G.M. (Eds.), Earth's Glacial Record. Cambridge Univ. Press, Cambridge, New York, pp. 146–161.

Williams, G.E., 1996. Soft-sediment deformation structures from the Marinoan glacial succession, Adelaide foldbelt: implications for the palaeolatitude of late Neoproterozoic glaciation. Sediment. Geol. 106, 165–175.

Williams, G.E., 1998. Late Neoproterozoic periglacial aeolian sand sheet, Stuart Shelf, South Australia. Aust. J. Earth Sci. 45, 733–741.

Williams, G.E., 2000. Geological constraints on the Precambrian history of the Earth's rotation and the Moon's orbit. Rev. Geophys. 38, 37–59.

Williams, G.E., Gostin, V.A., 2000. Mantle plume uplift in the sedimentary record: origin of kilometre-deep canyons within late Neoproterozoic successions, South Australia. J. Geol. Soc. (Lond.) 157, 759–768.

Williams, G.E., Gostin, V.A., 2001. Mantle plume uplift in the sedimentary record: origin of kilometre-deep canyons within late Neoproterozoic successions, South Australia: reply. J. Geol. Soc. (Lond.) 157, 759–768.

Williams, G.E., Schmidt, P., 2000. Proterozoic equatorial glaciation: has 'Snowball Earth' a Snowball's chance? Aust. Geol. 117, 21–25.

Williams, G.E., Tonkin, D.G., 1985. Periglacial structures and palaeoclimatic significance of a late Precambrian block field in the Cattle Grid copper mine, Mount Gunson, South Australia. Aust. J. Earth Sci. 32, 287–300.

Williams, G.E., Kasting, J.F., Frakes, L.A., 1998. Low-latitude glaciation and rapid changes in the Earth's obliquity explained by obliquity-oblateness feedback. Nature 396, 453–455.

Willis, B., 1944. Continental drift: Ein märchen. Am. J. Sci. 242, 509–513.

Wingate, M.T.D., Giddings, J.W., 2000. Age and paleomagnetism of the Mundine Well dyke swarm, Western Australia: implications for an Australia–Laurentia connection at 755 Ma. Precambrian Res. 100, 335–357.

Wingate, M.T.D., Pisarevsky, S.A., Evans, D.A.D., 2002. Rodinia connections between Australia and Laurentia: no SWEAT, no AUSWUS? Terra Nova 14, 121–128.

Winn Jr., R.D., Dott Jr., R.H., 1979. Deep-water-fan-channel conglomerates of Late Cretaceous age, southern Chile. Sedimentology 26, 203–228.

Winterer, E.L., 1963. Late Precambrian pebbly mudstone in Normandy, France. In: Nairn, A.E.M. (Ed.), Problems in Paleoclimatology. Interscience, London, pp. 159–178.

Wood, R.J., Edrich, S.P., Hutchison, I., 1989. Influence of North Atlantic tectonics on the large scale uplift of the Stapen High and Loppa High, Western Barents Shelf. In: Tankard, A.J., Balkwill, H.R. (Eds.), Extensional Tectonics and Stratigraphy of the North Atlantic Margins. Mem. - Am. Assoc. Pet. Geol., vol. 46, pp. 559–566.

Worsley, T.R., Kidder, D.L., 1991. First-order coupling of paleogeography and CO_2, with global surface temperature and its latitudinal contrast. Geology 19, 1161–1164.

Worsley, T.R., Moore, T.L., Fracticelli, C.M., Scotese, C.R., 1994. Phanerozoic CO_2 levels and global temperatures inferred from changing paleogeography. In: Klein, G.D. (Ed.), Pangea: Paleoclimate, Tectonics, and Sedimentation During Accretion, Zenith and Breakup of a Supercontinent. Spec. Pap. - Geol. Soc. Am., vol. 288. Geological Society of America, Boulder, pp. 57–73.

Wright, G.F., 1882. Man and the Glacial Period. International Science Library, A.L. Fowle, New York, 385 pp.

Yarnold, J.C., Lombard, J.P., 1989. A facies model for large rock-avalanche deposits formed in dry climates. In: Colburn, I.P., Abbott, P.L., Minch, J. (Eds.), Conglomerates in Basin Analysis: A Symposium Dedicated to A.O. Woodford [Book 62]. Pacific Section, Society of Economic Paleontologists and Mineralogists, Los Angeles, pp. 9–13.

Young, G.M., 1976. Iron formation and glaciogenic rocks of the Rapitan Group, Northwest Territories, Canada. Precambrian Res. 3, 137–158.

Young, G.M., 1988. Proterozoic plate tectonics, glaciation and iron formations. Sediment. Geol. 58, 127–144.

Young, G.M., 1992a. Late Proterozoic stratigraphy and the Canada–Australia connection. Geology 20, 215–218.

Young, G.M., 1992b. Neoproterozoic glaciation in the Broken Hill area, New South Wales, Australia. GSA Bull. 104, 840–850.

Young, G.M., 1993. Impacts, tillites and the breakup of Gondwana. A discussion. J. Geol. 101, 675–679.

Young, G.M., 1995. Are Neoproterozoic glacial deposits preserved on the margins of Laurentia related to the fragmentation of two supercontinents? Geology 23, 153–156.

Young, G.M., Gostin, V.A., 1988. Stratigraphy and sedimentology of Sturtian glacigenic deposits in the western part of the North Flinders Basin, South Australia. Precambrian Res. 39, 151–170.

Young, G.M., Gostin, V.A., 1989. An exceptionally thick upper Proterozoic (Sturtian) glacial succession in the Mount Painter area, South Australia. GSA Bull. 101, 834–845.

Young, G.M., Gostin, V.A., 1990. Sturtian glacial deposition in the vicinity of the Yankaninna Anticline, North Flinders Basin, South Australia. Aust. J. Earth Sci. 37, 447–458.

Young, G.M., Gostin, V.A., 1991. Late Proterozoic (Sturtian) succession of the North Flinders Basin, South Australia: an example of temperate glaciation in an active rift setting. In: Anderson, J.B., Ashley, G.M. (Eds.), Glacial Marine Sedimentation: Paleoclimatic Significance. Spec. Pap. Geol. Soc. Am. 261, 207–223.

Young, G.M., Long, D.G.F., Fedo, C.M., Nesbitt, H.W., 2001. Paleoproterozoic Huronian basin: product of a Wilson cycle punctuated by glaciations and a meteorite impact. Sediment. Geol. 141–142, 233–254.

Zhao, J., McCulloch, M.T., Korsch, R.J., 1994. Characterisation of a plume-related approximately 800 Ma magmatic event and its implications for basin formation in central–southern Australia. Earth Planet. Sci. Lett. 121, 349–367.

Zheng, Z., Yuhzen, L., Songnian, L., Huakun L., 1994. Lithology, sedimentology and genesis of the Zhengmuguan Formation of Ningxia, China. In: Deynoux, M., Miller, J.M.G., Domack, E.W., Eyles, N., Fairchild, I.J., Young, G.M. (Eds.), Earth's Glacial Record. Cambridge Univ. Press, Cambridge, pp. 101–108.

Ziegler, P.A., 1989. Evolution of the North Atlantic—an overview. In: Tankard, A.J., Balkwill, H.R. (Eds.), Extensional Tectonics and Stratigraphy of the North Atlantic Margins. Mem. Am. Assoc. Pet. Geol. 46, 111–130.

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