2.1 INTRODUCTION

The evidence preserved in sedimentary rocks suggests that ice ages were relatively rare on the early Earth, with only a single major glacial episode (Huronian Glacial Event) at about 2.3 Ga. The dearth of early glacial deposits may be interpreted in several ways. Perhaps surface temperatures were too high because of a high content of greenhouse gases in the atmosphere. On the other hand, if the Archaean Earth was subjected to cold periods, the lack of evidence in the geological record could merely reflect the paucity of continental lithosphere as a substrate for glaciers and the water-covered planet could have simply frozen. Glaciations were much more common in the last 750 Ma, when there were four major and several minor glacial episodes. The dearth of Archaean glacial deposits becomes even more puzzling when it is realized that the Sun was probably significantly less radiant (Sagan and Mullen, 1972), leading many to believe that Earth’s early atmosphere was charged with greenhouse gases such as carbon dioxide. The Cryogenian, Permo-Carboniferous, and Palaeogene-Recent glaciations are among the longest-lived and most extensive.

But for the fact that humans evolved during an ice age, ancient glaciations may have entirely escaped our attention. It was only through the energy and enthusiasm of early workers such as Agassiz (1842) that topographical and sedimentological criteria were developed for recognition of the former great extent of ice sheets in Europe and North America. With general acceptance of the radical idea that large areas of the Earth’s continents were recently under km-thick ice sheets, there were many attempts (some erroneous) to identify similar deposits among sedimentary rocks, as opposed to the unconsolidated debris left by Pleistocene glaciers. The first report of glacial deposits in Precambrian rocks is generally attributed to Thomson (1871) who discovered conglomerates in the Dalradian (mostly late Precambrian) succession on the island of Islay, in western Scotland, that he considered to indicate ancient glacial activity. Glacial deposits of the great Permo-Carboniferous event (Dwyka Formation and equivalents) were crucial among several lines of evidence used by du Toit (1937) to support the then-controversial theory of ‘continental drift’ (Wegener, 1912).

Field criteria used to identify glacial deposits in Precambrian rocks are relatively simple. They include massive diamictites which are conglomerates with a variety of clast types and sizes ‘floating’
in a finer matrix (Plate 2.1A), commonly known as ‘rock flour’, as it is derived from the crushing of rock material as abrasion takes place in, and at the base of, a moving ice mass. Striated and faceted stones are also used to identify glacial action, as are striated or grooved substrates, where clast-bearing ice masses overrode rocks or contemporaneous sediments. Finely laminated sedimentary rocks bearing isolated clasts (Plate 2.1B), showing signs of vertical emplacement (splash-up structures) are interpreted as ‘ice-rafted debris’ which may have been carried by floating glacier ice. There is a myriad of additional attributes that have been used to identify terrestrial glacial activity but these are only rarely preserved in Precambrian glacial deposits as they are highly susceptible to erosion and are commonly folded and metamorphosed. Most ancient glacial deposits are thought to have formed in marine settings. Some aspects of major element geochemistry, such as the Chemical Index of Alteration (CIA of Nesbitt and Young, 1982) have also been widely used to identify the unaltered nature of materials that commonly constitute ancient glacial deposits. In some cases age data from detrital zircons in glaciogenic rocks may be used as provenance indicators.

### 2.2 Age Distribution of Ancient Glacial Deposits

To find evidence of extensive glacial deposits older than those of the great Cryogenian glaciations (c. 730–630 Ma) we are obliged to look to the rocks of the Huronian Supergroup, which were
2.3 WHY DID GLACIATIONS OCCUR?

There have been many attempts to explain Earth’s sporadic cold periods. There are probably more ‘explanations’ than glaciations. Suggested causes of lowered surface temperatures include both extra-terrestrial and terrestrial mechanisms. Suggested extra-terrestrial causes include variable solar luminosity (Sagan and Mullen, 1972), the presence of Saturn-like rings forming a disc-shaped body around the Earth that cast shadows on some parts of the planet (Sheldon, 1984), passage of the solar system through ‘spiral arms’ of the galaxy (Shaviv, 2002; Shaviv and Veizer, 2003) and encounters with nebulae, such as supernova remnants and dark clouds (Kataoka et al., 2014). Since it was suggested by Sagan and Mullen (1972), by analogy with the known life cycle of other stars, that the Sun’s radiative power has been increasing throughout geological time, the dearth of glacial deposits in Archaean rocks has been widely attributed to a greater concentration of greenhouse gases such as CO₂ or methane in the early atmosphere. Geological evidence such as development of deep palaeosols and highly weathered sedimentary rocks such as quartz arenites in Archaean and Palaeoproterozoic successions points to the presence of a CO₂-rich atmosphere on the early Earth. The explanation of the Earth’s major glaciations, favored by the author, combines increasing solar luminosity with decreasing atmospheric CO₂ due, in part, to weathering as carbonic acid reacted with silicate minerals (mainly feldspar) at the surface of the Earth. The episodic nature of glaciations is attributed to different aspects of the supercontinental cycle (Nance and Murphy, 2013, and references therein). Because supercontinents are thermally buoyed they are susceptible to subaerial
weathering, which is greatly augmented during periods of uplift associated with rifting and break-up of a supercontinent, and during orogeny associated with assembly. The timing of glaciations in relation to the supercontinental cycle indicates that the Huronian and Cryogenian ice ages occurred during break-up (B-type glaciations), whereas the great Phanerozoic glaciations (Permocarboniferous and Palaeogene—Neogene) were triggered by orogenic activities associated with collisions during assembly of a supercontinent (A-type glaciations). The reasons for this difference are not immediately apparent but may reflect an increased susceptibility to glaciation as the CO₂ content of the atmosphere was reduced over time, so that younger glaciations could be triggered at an earlier stage in the supercontinental cycle (Fig. 2.2 and Box 2.2).
2.3 WHY DID GLACIATIONS OCCUR?

**FIGURE 2.2**

Palaeolatitudes of glaciogenic rocks through Earth history. Glacial episodes were much more common in the Phanerozoic Eon than in the Precambrian Era and occurred in high latitudes, whereas the older glaciations appear to have taken place in tropical latitudes (note the difference in time scale between the two). The change may have taken place in the late Ediacaran Period at around the time of the Acraman impact and a second possible impact at the time of development of the Shuram carbon isotopic anomaly. The small globes illustrate explanations that have been offered for the different palaeolatitudes of older and younger glacial deposits. The younger (grey background) glacial deposits formed under a moderate obliquity of about 23 degrees. Two explanations have been offered to explain the low latitudes of the older glacial deposits. These are the snowball Earth hypothesis (SEH) and the high obliquity theory (HOT). According to the SEH glaciers spread from polar to equatorial regions but, under the HOT they would have been initiated in tropical regions because of the Earth’s high obliquity (> 54 degrees). Abbreviations for supercontinents are as follows: Col, Columbia; Ken, Kenorland; Pan, Pangaea; Rod, Rodinia. See text for full discussion.
2.4 THE PALAEOLATITUDE PROBLEM

Over the last few decades data concerning palaeolatitudes at which ancient glacial sediments were deposited have shown that most Precambrian examples accumulated at low palaeolatitudes (Fig. 2.2) and it has also been shown that many formed in marine settings, indicating that glaciers were able to exist at, or close to, sea level in tropical regions (e.g., Embleton and Williams, 1986; Hoffman and Li, 2009; Evans, 2011). At the present day such conditions are only known from circum-polar latitudes and although glaciers are known to exist in low latitudes, they are unable to survive the high ambient temperatures at low altitude. Similar studies of glacial deposits of the Phanerozoic Eon have yielded quite different results showing that they were formed in high latitudes like those in Antarctica today.

Enigmatic palaeomagnetic results from Precambrian glacial deposits have sparked two opposing explanations. It was proposed by Kirschvink (1992) and Hoffman et al. (1998) that continental glaciers reached sea level in tropical latitudes because of runaway albedo, so that the entire surface of the Earth was encased in ice from pole to pole (the snowball Earth hypothesis or SEH). An alternative explanation was offered by Williams (1975, 2008). He proposed that glaciations could have taken place at low altitude and latitude as a result of the Earth having a differently inclined rotational axis relative to the plane of the Earth’s orbit (a high obliquity). According to the high obliquity theory (HOT), if the Earth entered a period of low surface temperatures, glaciation would first have affected areas at low latitudes because of the radically changed annual distribution of solar energy at the Earth’s surface. Problems posed by the apparent low palaeolatitudes of Proterozoic glacial deposits have not been definitively resolved. One remaining issue is the absence of evidence of glaciation at high latitudes, although it has been attributed to a dearth of continental lithosphere in the circum-polar regions. If this explanation is accepted (Fig. 2.3), then, according to the SEH, frigid conditions would have been initiated by freezing of the polar oceans. As ice development spread toward lower latitudes, it is inferred that the Earth entered a ‘runaway albedo’ condition, causing the entire surface of the planet to be frozen, with extensive ice sheets covering the continental masses, even though they were mostly located near to the equator (Fig. 2.3). The SEH thus involved initial development of sea ice that then spread toward continental areas at lower latitudes, where thick ice sheets later accumulated. This sequence of events, however, is unlikely because build-up of thick, extensive ice sheets requires a correspondingly massive source of moisture, which would have been precluded by the frozen condition of most of the world’s oceans (Fig. 2.3), making it most unlikely that melting of the postulated ice sheets could have brought about deposition of the thousands of metres of glaciogenic sediments preserved in many Precambrian basins (Box 2.3).

**BOX 2.2 WHY GLACIATIONS OCCURRED**

There is no completely satisfactory explanation for Earth’s glaciations. Both extra-terrestrial and terrestrial causes have been offered but both may have been important. Glacial epochs may be attributed to a combination of decreasing greenhouse gases (mainly CO₂) in the atmosphere and increasing solar radiation. It is suggested that glaciations may have been triggered by the cycle of amalgamation and dispersal of continental lithosphere – the supercontinental cycle.
(A) Depiction of two possible mechanisms for development of widespread glacial deposits in the Cryogenian Period. Sturtian palaeogeography is after Hoffman and Li (2009). According to the snowball Earth hypothesis glaciations began in high latitudes, where polar seas were frozen and ice extended to lower latitudes (arrows) and eventually affected continental regions which were mostly situated there. There may be a problem with the water budget in this model, as most oceanic areas would have been frozen when moisture was required to build up massive ice sheets. (B) An alternative model, based on the high obliquity theory which postulates that the spin axis of the Earth may have been much more steeply inclined throughout most of geological history, causing a radically different distribution of the Earth’s climatic belts. The model implies development and growth of ice sheets near the equatorial region and spreading toward higher latitudes (arrows). Under such a regime there would be an active hydrological regime for the polar regions which would have been ice-free for half of each year, when they were subjected to continuous solar radiation. See text for discussion.

**BOX 2.3 TROPICAL AND POLAR GLACIATIONS**

Precambrian glacial deposits, with the possible exception of some in the late Ediacaran Period, appear to have formed from glaciers that reached sea level in low palaeolatitudes whereas younger glaciations are only known from deposits that formed in circum-polar latitudes. This conundrum has not been resolved but has been attributed by some to ice cover that extended from pole to pole (the snowball Earth hypothesis). Others have suggested that marked tilting of the Earth’s spin axis, in the Precambrian, could have changed the distribution of annual solar energy, causing glaciations to occur preferentially at low latitudes.
Using the Cryogenian (Sturtian) palaeogeography proposed by Hoffman and Li (2009), the HOT predicts a quite different set of climatic conditions. As the Earth entered a frigid period abundant moisture from the polar oceans would have fed developing glaciers at low latitudes, causing them to expand toward higher latitudes with time (Fig. 2.3). The envisaged system would have involved a highly active hydrologic system, producing thick, dynamic continental glaciers capable of producing the thick, stratigraphically complex, glaciogenic successions found in the geological record. Termination of these great Precambrian glaciations was attributed by adherents of the SEH to build-up of atmospheric CO$_2$ from on-going volcanic activity, and decreased drawdown because of greatly diminished weathering and photosynthetic activity. The same mechanism can be invoked under the HOT, except that the absence of year-round frozen oceans, as invoked under the SEH, would have allowed much more efficient diffusion of gaseous volcanic emanations from ocean to atmosphere.

### 2.5 ARCHAEOAN GLACIATIONS

There is little definitive evidence of Archaean glacial activity. The most convincing deposits are found in South Africa, where diamictites and laminated mudstones containing ‘outsise’ clasts (dropstones) occur together and testify to the existence of Archaean ice sheets in the Pongola Supergroup, which was deposited at about 2.9 Ga (Young et al., 1998, and references therein). These, together with possible correlatives in the Witwatersrand basin to the west and other possible locally preserved glacial deposits elsewhere (Hambrey and Harland, 1981) provide scant evidence of glaciation during the long, early (Archaean) part of Earth history. The dearth of Archaean glacial deposits is enigmatic, considering that the Sun may have been about 30% less radiant than it is today but, as noted above, the Earth probably was enveloped by a CO$_2$-rich atmosphere that would have retained a high proportion of the thermal energy arriving at its surface.

### 2.6 PALAEOPROTOEREOZOIC GLACIATIONS

#### 2.6.1 DISTRIBUTION

Evidence of widespread frigid climatic conditions is present in some Proterozoic rocks, but such deposits are known from only two quite short time intervals near the beginning and end of that eon. Palaeoproterozoic glacial deposits are known from North America, Karelia, South Africa, Western Australia, and India but those of the Huronian Supergroup are probably the most well known, having been the subject of numerous investigations since their early recognition by Coleman (1907). A summary of the history of these investigations was provided in Young (2013a).

#### 2.6.2 THE HURONIAN SUPERGROUP, ONTARIO, CANADA

The Huronian Supergroup (up to 12 km thick) is preserved in a fold belt on the southern margin of the exposed Canadian shield (Fig. 2.4). The lower age limit of Huronian deposition is close to that of the Thessalon Volcanic Formation (Fig. 2.5) and equivalents, which have yielded dates of 2450 ± 25 (Krogh et al., 1984) and 2452.5 ± 6.2 Ma (Ketchum et al., 2013). The time of deposition
of the youngest Huronian formation is not precisely known but the supergroup is extensively intruded by sills, sheets, and dikes of the Nipissing diabase suite, which has been dated at 2217 ± 9 Ma (Corfu and Andrews, 1986). No precise dates are available from any sedimentary formations of the Huronian Supergroup but, in neighbouring Michigan, Vallini et al. (2006) obtained dates of 2317 Ma from zircons in the glaciogenic Enchantment Lake Formation, which has been considered to be correlative to the Gowganda Formation (Young, 1970). These dates either provide

**FIGURE 2.4**

Sketch map to show the distribution of the Huronian Supergroup in the area north of Lake Huron, Ontario. Note that formations belonging to the lower Huronian (below the Gowganda Formation) are confined to an area south of the Flack Lake Fault, considered to have been a rift basin at the time of deposition. The upper Huronian succession, beginning with the glaciogenic Gowganda Formation, is considered to have formed at a developing marine margin.
Schematic north—south cross-section through the Huronian fold belt to show the limited distribution of lower Huronian formations in a rift basin and the more widespread distribution of the marine upper Huronian, beginning with the Gowganda Formation. The column (centre) represents the stratigraphic succession of the Huronian Supergroup, showing the three glaciogenic formations. Column at right is a stratigraphical column representing the Gowganda Formation in the southern part of the Huronian fold belt. Note that there are two diamicite-bearing units representing two glacial advance—retreat cycles and that the upper part of the Gowganda Formation is a postglacial deltaic complex.
the depositional age of that formation (as suggested by Vallini et al., 2006) or could indicate that the formation is younger than that age. Thus the age of the Gowganda Formation remains uncertain but it may have been deposited at about 2317 Ma or it may be younger than that date. The age of the Gowganda Formation is of special importance because there have been numerous attempts to correlate it to Proterozoic glacial deposits around the world (see Young, 2014, for references and a discussion of these problematic correlations). Almost 50 years ago it was realized (Young, 1966, 1970) that Palaeoproterozoic glacial deposits comparable to those in the Huronian Supergroup (especially the Gowganda Formation) are present in a huge area of North America, stretching ~2000 km to Wyoming in the southwest and a similar distance to Nunavut on the west side of Hudson Bay (Fig. 2.6). Similar glacial deposits are present at Chibougamau in northern Quebec (Long, 1974). Although these lithostratigraphically based correlations were initially rejected by
many, subsequent geochronological work has provided confirmation (Karlstrom et al., 1984; Aspler and Chiarenzelli, 1997; Vallini et al., 2006).

The Huronian stratigraphic succession in the southern part of the eponymous outcrop belt includes three units that have been considered as glacial in origin. These are, in ascending order, the Ramsay Lake, Bruce, and Gowganda formations (Fig. 2.5). There are, however, significant differences between the Gowganda Formation and the two older glaciogenic units. For example, the Ramsay Lake and Bruce formations are confined to the southern part of the Huronian outcrop belt on the south side of east-west faults that are considered to represent the northern limits of a rift basin, whereas the Gowganda and succeeding formations overstep these formations to lie directly on the Archaean basement over a large area that lay to the north of the rift basin. The stratigraphy of the two lower diamictite-bearing formations is much simpler than that of the thicker Gowganda Formation and the older diamictites have sand-grade quartz-rich matrices. Whereas none of the formations below the Gowganda contains unequivocal evidence of marine conditions, the widespread Gowganda and succeeding formations do (Lindsey, 1971; Young and Nesbitt, 1985; Young, 2014, and references therein). Among the earliest workers to carry out a detailed study of sedimentary conditions during deposition of the Gowganda Formation, Lindsey (1969, 1971) proposed that it was possible to differentiate between continental facies to the north and marine deposits to the south. It was argued by Miall (1983) that the Gowganda Formation in the northeastern part of its outcrop belt was marine. A detailed account of the stratigraphy/ sedimentology of the southern part of the Gowganda Formation was provided by Young and Nesbitt (1985). Together with the early work of Lindsey (1971) this study revealed the complex stratigraphy of the formation, involving two glacial advance—retreat cycles, separated by a thick nonglacial laminated and finely bedded argillite. The two diamictite-bearing units show abundant evidence of ‘resedimentation’ processes and contemporaneous fault activity. The formation is about 1500 m thick in the southern area but the upper half is a complex assemblage of coarsening upward cycles that shows no evidence of glacial influence and is interpreted as postglacial deltaic deposits (Rainbird and Donaldson, 1988; Junnila and Young, 1995).

The Huronian Supergroup is a thick, dominantly siliciclastic succession that includes three glaciogenic formations. The lower part of the succession is thought to have been deposited during a protracted rift episode that culminated, at the time of deposition of the Gowganda Formation, in development of a passive margin and influx of marine waters. The Huronian succession also contains evidence of oxygenation of the atmosphere as spelled out by Roscoe (1973) on the basis of field characters, such as the occurrence of fluvial pyritic sandstones and quartz-pebble conglomerates near the base, and the appearance of red beds in the Lorrain Formation above the glacial and deltaic deposits of the Gowganda Formation. Thus the important transition that has come to be known as the Great Oxidation Event (Holland, 2006) appears to have taken place during deposition of the Huronian Supergroup (Box 2.4).

**BOX 2.4 THE HURONIAN GLACIAL EVENT**

The Earth’s first widespread glaciation is recorded in the Palaeoproterozoic Huronian Supergroup, which contains three glacial formations. The youngest of these is widely distributed in North America and possibly elsewhere in the world. The Huronian Glacial Event took place when the late Archean supercontinent, Kenorland, was breaking apart and may therefore be the first ‘B-type’ glaciation.
2.6.3 CORRELATIVES OF THE GOWGANDA FORMATION

For over 50 years (Pettijohn, 1943) Proterozoic glacial rocks have been recognized on the south shore of Lake Superior and were correlated to the Gowganda Formation (Young, 1970). These correlations are now supported by geochronological data. Glacial deposits of similar age are now known to be widespread in North America, but the closest similarities to the entire Huronian Supergroup exist in southeastern Wyoming. It was proposed by Roscoe and Card (1993) that the near-identical Wyoming succession (Snowy Pass Supergroup) may be the ‘other side’ of the Huronian basin, rifted away during continental break-up and rotated into its present position. An alternative interpretation is that the two identical successions were developed along the same continental margin in places where they had similar tectonic and climatic histories (Young, 2015a). The locations of some of these areas are shown in Fig. 2.6 and representative stratigraphic columns in Fig. 2.7. It was suggested by Young (1970) that these widely separated occurrences of Palaeoproterozoic glacial deposits (especially the more extensive Gowganda Formation and correlatives) may have been produced from a single widespread continental ice sheet. As pointed out by Strand (2012) the existence of marine conditions during glaciation is important as it indicates that it probably took the form of a large continental ice sheet, as opposed to local ice accumulations such as those on mountains or on rift shoulders. Marine glaciation is also important because, if related to a substantial body of ice, it should affect world sea levels, thus potentially facilitating long-distance correlations. Relationships among Palaeoproterozoic glaciogenic rocks of North America are also strengthened by the presence, above the correlated glaciogenic units, of unusual alumina-rich quartz arenites, suggesting that the widespread glaciations were followed by conditions conducive to strong weathering, probably under a CO$_2$-charged atmosphere. The presence of red beds in the postglacial formations suggests that atmospheric oxygen had reached the point where the ferrous–ferric transition was supported (Roscoe, 1973; Rainbird et al., 1990).

All of the Palaeoproterozoic rocks considered earlier, with the possible exception of the Hurwitz Group on the west side of Hudson Bay (Aspler and Chiarenzelli, 1997) may have formed along the same continental margin (Fig. 2.6) and appear to have been deposited during break-up of a supercontinent or ‘supercraton’ known as Kenorland (Williams et al., 1991). Thus the ‘Huronian Glacial Event’ took place, at least in North America, during break-up of a supercontinent and is therefore designated as a B-type glaciation.

2.6.4 PALAEOPROTEROZOIC GLACIAL DEPOSITS BEYOND NORTH AMERICA

Early Palaeoproterozoic glacial deposits are also known from Finnish and Russian Karelia (Marmo and Ojakangas, 1984; Strand, 2012; Melezhik et al., 2013). These rocks may have formed in fault troughs related to break-up of a supercontinent and their age constraints indicate that some of them may have been contemporary with the Huronian Glacial Event. Glacial rocks of similar age to the Huronian Supergroup have also been reported from India (Mohanty, 2006).

Palaeoproterozoic glacial deposits are known from southern Africa and Western Australia, which have been considered by some to have formed a single continental mass known as Vaalbara (Cheney, 1996). There have been various attempts to effect correlations with the Huronian formations in Canada (Rasmussen et al., 2013; Hoffman, 2013; Eriksson and Altermann, 2013; Tang and Chen, 2013). As pointed out by Young (2014) these attempts are commonly contradictory as the
FIGURE 2.7
Stratigraphical logs to represent the Palaeoproterozoic successions in some of the basins shown in Fig. 2.6. Note the remarkable similarity between the Huronian and Wyoming basins, which some have suggested were previously juxtaposed. The Gowganda Formation and overlying aluminous quartz arenites provide a common link among the basins. Red ornament at the top represents the rise of atmospheric oxygen following the end of the Huronian Glacial Event.
Huronian glaciogenic formations, none of which has been precisely dated, have been correlated to different units of a single succession in other countries. In addition, the older Huronian glacial formations (Ramsay Lake and Bruce formations) may have been quite local as they are found only in the Huronian rift basin and in southeastern Wyoming in North America.

Glacial deposits of the Makganyene Formation in the Transvaal Basin of South Africa were considered by Kirschvink et al. (2000) to have formed during a global glaciation, comparable to the so-called ‘snowball Earth’ events proposed by some for the widespread Neoproterozoic events. An extremely widespread Makganyene glaciation was also supported by Kopp et al. (2005) and Hilburn et al. (2005) who suggested that this event was entirely younger than the Huronian glaciations. It is, however, problematic that this supposedly global glaciation, in contrast to the widespread outcrops representing the Huronian Glacial Event and the Cryogenian glaciations, appears to have left a record in only one place. It was proposed (Bekker et al., 2001, 2005) that the glacial deposits of the Gowganda Formation might be equivalent to those of the Makganyene and upper Timeball Hill Formations in South Africa (Fig. 2.8) and they tentatively suggested that diamictites in the lower Duitschland Formation may be equivalent to the Bruce Formation because...
both are overlain by carbonate rocks considered to be analogous to ‘cap carbonates’ that commonly occur above Neoproterozoic glacial deposits.

Palaeoproterozoic glaciogenic deposits were reported from Western Australia by Trendall (1976, 1979). Martin (1999) confirmed this interpretation but noted that the Meteorite Bore Member of the Kungarra Formation also contains turbidites and mass flow deposits. These rocks are underlain by iron-rich rocks of the Hamersley Group which also contain possible glaciogenic deposits, interpreted by Swanner et al. (2013) as representing a separate, older glacial event. The age of the Meteorite Bore Member is between about 2.45 and 2.21 Ga (Martin, 1999; Lepland, 2013). Recent investigations of the Western Australian localities (Mazumder et al., 2015; Van Kranendonk and Mazumder, 2015) support the idea of two separate glacial units within the Kungarra Formation of the Turee Creek Group and have documented the presence of three falling stage system tracts in the Turee Creek Group and two glaciations that they considered to have effected large-scale (at least tens of metres) changes in global sea level. The basinal setting of Palaeoproterozoic glacial deposits in both South Africa and Western Australia is uncertain but Van Kranendonk and Mazumder (2015) considered the latter area to have been relatively stable, so that inferred sea level changes were probably glacio-eustatic. It is interesting to compare these results with the situation in the Gowganda Formation (e.g., Young and Nesbitt, 1985), which contains evidence of two discrete glacial episodes, separated by a thick argillite that shows no physical evidence of glacial influence, apart from a few small dropstones near the base and top. Both diamicite-bearing units in the Gowganda Formation show abundant evidence of ‘re-sedimentation’ processes in the form of slumped beds and turbidites. The second glacial retreat was followed by deposition of a series of deltaic deposits. Thus, although the Gowganda Formation was deposited in a more tectonically active environment, its stratigraphy can be interpreted in terms of climatic and sea level changes similar to those in Western Australia. Some authors have attributed deposition of Palaeoproterozoic glacial sediments, both in South Africa and Western Australia, to foreland basin settings. It was proposed by Visser (1971) that some of the South African Palaeoproterozoic glacial deposits were shed from an elevated interbasinal area (the Vryburg Ridge) although others have favored a foreland basin. The depositional setting of glacial deposits in both South Africa and Western Australia is still debated but it may have been rather similar to that envisaged for the Huronian Basin. Indeed if the two glacial episodes recognized in the Gowganda Formation involved global sea level fluctuations then it is possible that they may correspond to those in the Turee Creek Group but this can only be confirmed or refuted by definitive geochronological studies.

2.7 THE BARREN BILLION

Because of the dearth of glacial deposits and iron formations, and the relatively invariant geochemical signals used as proxies for changes in the composition of the oceans and atmosphere, the period between about 1.8 Ga and 800 Ma has been referred to as the ‘boring billion’ (Holland, 2006) or ‘barren billion’ (Roberts, 2013; Young, 2013a,b). This huge time span was, however, far from boring in regard to tectonic activity, as it saw the birth and demise of what some have called the first true supercontinent, Columbia, and assembly of the great supercontinent, Rodinia (Rogers and Santosh, 2002; Roberts, 2013).
Throughout this long period there is little evidence of glacial activity, although there are reports of glacio-fluvial and periglacial features in Western Australia (Williams, 2005) and central Sweden (Kuipers et al., 2013) at between 1.8 and 1.7 Ga. Both were reported to have formed at low palaeolatitudes. An occurrence of late Mesoproterozoic glaciation was recorded by Geboy et al. (2013) from Brazil. These deposits were interpreted as having formed at relatively high latitudes, between 40 and 60 degrees south. The significance of the dearth of evidence of glaciations during the barren billion is difficult to evaluate. It was attributed by Eyles (2008) to lack of preservation but this seems unlikely in light of the widespread record of glaciations preserved on other, older supercontinents.

2.8 THE GREAT CRYOGENIAN GLACIATIONS

The Cryogenian glaciations were probably the most severe and widespread in Earth history. These glaciations inspired the term ‘snowball Earth’ (Kirschvink, 1992; Hoffman et al., 1998), although the idea of very widespread Precambrian glaciations is much older (Mawson, 1949; Harland, 1964; Young, 1970). In many areas throughout the world there is stratigraphical and geochronological evidence of at least two very extensive glacial episodes that were named the Sturtian and Marinoan glaciations from localities in South Australia. These deposits are far too numerous to describe individually but compilations of these occurrences are given in Hambrey and Harland (1981) and Arnaud et al. (2011). For a summary of their distribution in time see Fig. 2.1 and a reconstruction of palaeogeography at the time of the Sturtian glaciation is shown in Fig. 2.3 (after Hoffman and Li, 2009). Although there is evidence of a wide range of ages, the Cryogenian occurrences were considered by Hoffman and Li (2009) to have occurred at between 727 and 654 Ma (Sturtian) and between 660 and 635 Ma (Marinoan), so that the two glaciations could have overlapped slightly in time.

Many Sturtian glacial deposits accumulated and were preserved in rift basins (Eisbacher, 1978; Yeo, 1981; Young, 1995; Preiss, 2000) that heralded the break-up of the supercontinent Rodinia, like those of the much older Huronian Supergroup (Young, 2014). Many Sturtian glaciogenic deposits are associated with iron formations, which is remarkable because such rocks are not found in the geological record for the previous billion years. Two origins have been proposed for these young iron formations. According to the SEH these iron formations resulted from build-up of ferrous iron in solution in oceans that were isolated from the oxygenated atmosphere by a thick ice cover. When the ice disappeared reintroduction of oxygen to the oceans caused precipitation of iron (Klein and Beukes, 1993). Others, such as Yeo (1981) and Cox et al. (2013) suggested that the Sturtian iron formations formed as a result of hydrothermal activity in rift basins formed during fragmentation of Rodinia, an idea that is supported by the common association of Sturtian glacial deposits with mafic volcanic rocks.

Another odd association, most commonly found in the Marinoan glacial deposits (Hoffman, 2011), is the juxtaposition of carbonate rocks (mostly dolostones) above diamictites. Many cap carbonates are stromatolitic, contain large-scale wave ripple structures (Allen and Hoffman, 2005), and some have small vertical pipe structures. These unusual carbonate rocks have been linked by some to unusual conditions at the end of the Marinoan glaciation, when CO$_2$ levels in the
atmosphere were thought to have been exceptionally high. These so-called ‘cap carbonates’ are still poorly understood but the base of one such unit was taken as the boundary between the Cryogenian and Ediacaran periods (Knoll et al., 2006).

Since low depositional palaeolatitudes were proposed for Cryogenian glacial rocks in South Australia (Embleton and Williams, 1986) many similar results have been reported from Neoproterozoic glacial deposits in various parts of the world, as summarized by Hoffman and Li (2009) and Evans (2011). Deposition of glacial deposits at or near sea level in low latitudes was one of the main cornerstones of the SEH (Kirschvink, 1992; Hoffman et al., 1998) but an alternative explanation was offered by Williams (1975, 2008). He interpreted the occurrence of ice sheets at sea level in tropical latitudes as the result of a radically different distribution of climatic zones, brought about by a significant increase in the tilt of the Earth’s spin axis. It was argued that if the Earth descended into a glacial phase when the tilt of its spin axis (obliquity of the ecliptic) exceeded 54 degrees, the annual heat distribution across the surface of the planet would cause glaciers to develop preferentially in tropical latitudes. The highly tilted spin axis was thought to have been produced by the large impact that has been invoked to explain the origin of the Moon. The timing of, or mechanism responsible for bringing the Earth to its present obliquity is unknown, although there appears to be a difference between palaeolatitudes at which both the Huronian and Cryogenian glaciations occurred and those of late Ediacaran and all Phanerozoic ones.

The two great Cryogenian glaciations appear to have taken place under tectonic circumstances similar to those of the early Palaeoproterozoic Huronian Supergroup, namely during disintegration of a supercontinent. Fragmentation of Rodinia was prolonged, with initial rifting (accompanying the Sturtian glacial episode) taking place mainly on the west side of North America and the second, possibly overlapping, rift episode on the east side when the Marinoan glaciation took place (Box 2.5).

2.9 EDIACARAN ICE AGES

The recently defined Ediacaran Period extends from 635 to 541 Ma, which is taken as the age of the base of the Cambrian. It begins at the end of the second great Cryogenian glaciation and ends at the time when the widespread and prolific shelly metazoan fauna appears during what has been called the ‘Cambrian Explosion’. The Ediacaran Period was a time of great environmental change including several glacial episodes, at least one large meteorite impact, changes in the chemistry of the atmosphere and oceans, puzzling palaeomagnetic indicators that have been interpreted by some to reflect rapid true polar wander, and evolutionary changes that led to the burgeoning of the skeletonized metazoan fauna that went on to colonize the world.
As noted earlier, the period was ushered in with demise of the extensive Marinoan ice sheets. About 50 million years later the Earth entered a brief glacial episode known as the Gaskiers glaciation at about 580 Ma (Narbonne et al., 2012; Young, 2015b, and references therein). The Ediacaran Period is characterized by four negative $^{13}$C$_{\text{carbonate}}$ excursions (Fig. 2.9), some of which may be associated with glaciations. The oldest is probably related to the Marinoan glacial episode. The second isotopic anomaly is considered to be about the same age as the Gaskiers glacial episode and the large Acraman impact (Williams, 1986) that occurred in South Australia at about 580 Ma (Gostin et al., 2011).

**FIGURE 2.9**

Some important environmental parameters of the Ediacaran period and their possible influences on the evolution of life as a result of a series of radiations and extinctions. Note that several negative $^{13}$C excursions appear to coincide with glaciations but more isotopic, palaeomagnetic, geochronological, and sedimentological data are required to better understand the important environmental changes that occurred during the Ediacaran Period that was the cradle for most higher life forms, whose presence only became clearly apparent with development of exoskeletons during the so-called ‘Cambrian Explosion’. Green colour represents leiospheres, blue indicates acanthomorphic acritarchs. Abbreviations are as follows: A.I., Acraman impact; Cryog., Cryogenian Period; EXT, extinction event; RAD, biological radiation; S.I?, putative Shuram impact.

The third $\delta^{13}C$ anomaly, known as the Shuram or Wonoka anomaly, was probably the greatest and possibly the most long-lived in the geological record (Le Guerroué et al., 2006; Young, 2015b). The Shuram anomaly was a worldwide phenomenon for which no completely satisfactory explanation has been advanced. Some have invoked stepwise oxygenation of the oceans, and it was tentatively suggested (Young, 2015b, and references therein) that the oxygenation of the oceans and contemporaneous geological events such as excavation of deep canyons in South Australia (Von der Borch et al., 1989), biotic extinction events, and the unusual asymmetrical shape of the anomaly (Fig. 2.9) might be explained as resulting from a large marine impact. There is no direct evidence that the putative impact was accompanied by glaciation, apart from the suggestion by Hebert et al. (2010) that a post-Gaskiers glaciation in Virginia, USA (Fauquier glaciation) occurred at about 570 Ma, following deposition of limestones with strong negative $\delta^{13}C$ values (Box 2.6).

The final $\delta^{13}C$ anomaly of the Ediacaran Period and Precambrian Era took place close to the Lower Cambrian boundary. Like the other anomalies described above it too was associated with glaciations. Evidence of late Ediacaran glaciation was reported by Vernheta et al. (2012) from the Bou-Azzer region in the Anti-Atlas of Morocco in North Africa. They suggested that these glacial deposits were formed at a high palaeolatitude and were laid down at about 560 Ma. There are several other reports of latest Ediacaran glacial deposits in west Africa (Caby and Fabre, 1981; Bertrand-Sarfati et al., 1995; Deynoux et al., 2006). These glaciations are all thought to have taken place at high palaeolatitudes according to palaeogeographic reconstructions by Li et al. (2008). Similar late Ediacaran glaciations were reported by Chumakov (2009, 2011a,b) and Chumakov et al. (2011) in parts of the Russian Federation. Thus there is evidence of several short-lived Ediacaran glaciations. The Gaskiers (and possibly the Fauquier glaciation) may have occurred at about the same time as large impacts (Acraman at about 580 Ma and the putative Shuram impact at about 570 Ma). Still younger, later Ediacaran glaciations have been reported from a number of locations. Almost all of the Ediacaran glacial deposits require more geochronological and palaeomagnetic studies.

### 2.10 TECTONIC SETTING AND PALAEOLATITUDES: RADICAL CHANGES IN THE EDIACARAN PERIOD

A change in tectonic setting (and palaeolatitudes) of glacial deposition probably occurred sometime in the Ediacaran Period, but more data are needed to determine the precise timing of these important changes. Almost all widespread Precambrian glaciations occurred in the early Proterozoic Eon.
(Siderian) and in the Cryogenian Period but there were frequent glacial episodes throughout the latter part of the Ediacaran Period and during Phanerozoic time (Fig. 2.1) The tectonic setting of most Proterozoic glacial deposits also differs from that of their Phanerozoic counterparts for geological investigations and radiometric dating show that most Proterozoic glaciations (Huronian and Cryogenian) occurred during the demise (break-up) of supercontinents, whereas the most significant Phanerozoic glaciations (Permo-Carboniferous and Palaeogene–Neogene) took place during periods when supercontinental assembly was underway. This difference, and indeed the more frequent occurrence of glaciations in the last 600 Ma of Earth history, may be a function of the decreasing amount of atmospheric CO$_2$. For example, in the Huronian Supergroup glaciations could not take place until both orogeny during assembly, and weathering during erosion of the supercontinent, Kenorland, had brought atmospheric CO$_2$ below the threshold value at which glaciations could occur, triggered apparently by uplift during break-up. By the Phanerozoic Eon (and probably during the late Ediacaran Period) the amount of CO$_2$ in the atmosphere was sufficiently low that glaciations could be triggered more readily, during orogenesis accompanying supercontinental assembly. Thus the Permo-Carboniferous glaciations followed closely on the Taconic, Acadian, Caledonian, and Variscan orogenies and the Palaeogene-present glaciation may be tied to the Alpine-Himalayan orogenies which are thought to be largely due to northward movement of India and Africa and their collisions with Eurasia.

Another stark contrast between Precambrian and Phanerozoic major continental glacial episodes is that the former appear to have occurred at low palaeolatitudes, whereas the Phanerozoic occurrences (and some of the late Ediacaran examples) took place in circum-polar latitudes. This difference lies at the core of debates concerning the SEH, which supports complete or near-complete freezing of the Earth’s surface, and the HOT, which explains the low-latitude glaciations as being due to preferential cooling of Earth’s low-latitudinal regions as a result of the Earth’s spin axis being tilted at a high (> 54 degrees) angle during most of the Precambrian Era (Box 2.7).

One important issue in the debate surrounding the question of Precambrian glaciations at low palaeolatitudes is the timing of the change to Phanerozoic-style glaciations. The available data regarding precise radiometric ages and reliable palaeomagnetic information are fragmentary but suggest that the change in glacial style (regardless of its cause) may have occurred between the Gaskiers and Fauquier glaciations, at about 570 Ma, in the late Ediacaran. The mechanism responsible remains obscure but geophysical evidence (Kirschvink et al., 1997; McCausland and Hodych, 1998; Hoffman, 1999) suggests that the Earth may have undergone inertial interchange true polar wander in late Ediacaran time. This process is thought to have involved rotation of the entire silicate shell of the Earth

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**BOX 2.7 COMPARISONS AND CONTRASTS**

In contrast to most great Precambrian glaciations those of the Phanerozoic Eon took place much earlier in the supercontinental cycle, during orogenic phases that accompanied assembly of the supercontinent. They are called, ‘A-type’ glaciations. The ‘early’ appearance of the younger glacial episodes may be due to the greatly reduced CO$_2$ content of the atmosphere. The other great difference is the switch from tropical glaciations, which have been attributed by some to snowball Earth conditions, to high-latitude, circum-polar glaciations, This change has also been explained as the result of a change in the tilt of the Earth’s spin axis (the high obliquity theory). Neither explanation is universally accepted but the changes appear to be real.
down to the core—mantle boundary. This mechanism is thought to have been capable of bringing about significant change in the obliquity of the ecliptic (Prévot et al., 2000). It was suggested (Young, 2013b, 2014) that the Earth may have suffered a large marine impact at the time when the Shuram negative δ13C excursion was developed (at about 570 Ma?) (Fig. 2.9) and although the proposed impactor is unlikely to have been sufficiently large to significantly change the orientation of the planet’s spin axis, it may have caused displacement (avalanching) of a large portion of the oceanic lithosphere and initiated inertial interchange true polar wander that could have brought about such a change (Prévot et al., 2000). These speculations are offered as a potential alternative to the SEH but it must be recognized that the differences between most Proterozoic (low-latitude) glaciations and the circum-polar Phanerozoic glaciations remain one of the greatest puzzles of palaeoclimatology (Young, 2013b).

2.11 CONCLUSIONS

Extensive Precambrian glaciations were infrequent, occurring only near the beginning (Huronian Glacial Event) and end (Cryogenian glaciations) of the Proterozoic Eon. Glacial episodes were much more frequent during the Phanerozoic Eon. The great Precambrian glaciations occurred during the disintegration of the supercontinents Kenorland and Rodinia but the intervening supercontinent, Columbia, has not yet provided evidence of widespread glaciation. These glaciations are mostly preserved in rift basins and on passive margins that developed during break-up of supercontinents. Palaeomagnetic data from Proterozoic glacial deposits suggest that they were laid down in circum-equatorial zones. All of these attributes stand in marked contrast to the most widespread Phanerozoic glaciations which appear to have formed during orogenesis leading to assembly of supercontinents (Pangaea and ‘Amasia’) and had a circum-polar distribution. The radical difference in tectonic environment—at the end of a period of supercontinentality in most of the Precambrian and at its initiation in the Phanerozoic—may be due to diminishing CO2 levels in the atmosphere so that a much more prolonged period of weathering was required for Precambrian temperatures to drop below the glacial threshold. The different latitudinal distributions of Precambrian and Phanerozoic glacial deposits have not been definitively explained. Proponents of the SEH maintain that low palaeolatitudes from the older glacial deposits indicate that most of the planet’s surface was glaciated or frozen. The lack of glacial deposits at high latitudes is explained by invoking a dearth of continental lithosphere in these areas but it is not clear why such a distribution should have existed for so long. The alternative suggestion is the HOT of Williams (1975) which posits that the low latitudes of Precambrian glaciations were due to a completely different distribution of climatic zones on the planet due to its having a much higher obliquity. More sedimentological, geochronological, and palaeomagnetic investigations are required before the contrasting tectonic and palaeolatitudinal settings of Precambrian and Phanerozoic glaciations can be rationalized. The timing and nature (sudden or gradual) of the transition between the two glacial styles will also shed light on its cause. It is suggested here that the change was quite rapid and occurred near the middle of the Ediacaran Period but the timing, palaeolatitudes, and even the number of Ediacaran glaciations are all in need of careful scrutiny. Many advances have been made in the study of Precambrian glacial deposits in the last two decades so that important questions may now be asked, but answers must await the results of future research.
Glaciations played an extremely important role in the oxygenation of the atmosphere and oceans by fertilization of the oceans with essential nutrients during deglaciations and triggering unprecedented photosynthetic blooms. Having played an important role in providing one essential ingredient for the rise of higher life forms (metazoans), glaciations also contributed to the environmental upheavals that may have accelerated evolutionary processes leading to the ‘Cambrian Explosion’ of higher life forms. Thus the existence of glacial episodes and the evolution of higher life forms on Earth and other similar planets may be predicated on the existence of a dynamic interior that powers plate tectonics and the resultant supercontinental cycle. The sad corollary is that when plate tectonics grinds to a halt due to cooling of the Earth’s interior, and CO₂ is withdrawn from the atmosphere by weathering, photosynthetic activity (and oxygen production) will decrease and all higher, oxygen-based, life forms will disappear from the surface of the planet and the human experiment on Earth will be terminated.

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