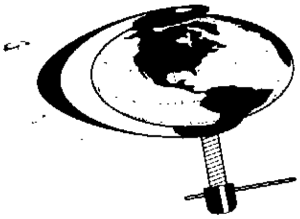

The Geologic Record of Glaciation: Relevance to the Climatic History of Earth

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SUMMARY

The only long-term record of climatic change is the geologic record, which suggests that the surface of the planet has had a remarkably stable thermal history. This stability is remarkable because of an inferred 30% increase in solar luminosity since Early Archean time. The glacial record provides some of the best evidence of thermal perturbation. The major cause of glaciation may be the periodic reduction of atmospheric CO_2, which is linked, *via* plate tectonics, to the weathering cycle. Different glacial epochs may, however, have had different controls. Early Proterozoic glaciation may have occurred because of the combination of enhanced weathering of newly emergent cratons, and the faint early sun. Associated highly weathered rocks may reflect the high CO_2 content of the atmosphere. Late Proterozoic glaciation is explained as being due to lowering of atmospheric CO_2 levels by extreme weathering of a supercontinent at low latitudes. Most Phanerozoic glaciation was caused by the combined effects of weathering of an elevated supercontinent (Pangea) and polar positioning. The Cenozoic glaciation may be related to high latitudes of some continental masses and reduced CO_2 levels due to enhanced weathering of the continents which become emergent as the Atlantic Ocean floor ages, cools and sinks. What of the future? In the short term, the "Little Ice Age" climatic cycle suggests warming for about the next 1,000 years. Global cooling should follow as the Earth descends into the next severe glaciation predicted by Milankovitch theory. Anthropogenic contribution to the greenhouse effect should enhance the short-term warming trend. The repeated cycle of Cenozoic glaciations will end with the initiation of subduction along the Atlantic margins.

INTRODUCTION

Sparked largely by records of atmospheric CO_2 content over the last three decades and by the discovery of a recurring hole in the ozone layer above the Antarctic continent, there has been revival of interest in the old idea (going back at least to 1863) that trace amounts of atmospheric gases can have a profound influence on conditions at the surface of the planet. The fact that the decade of the 1980s was the hottest on record has also generated considerable interest and apprehension and there has been an ever-increasing tendency to propose a link between rising global temperature and concentrations of greenhouse gases, notably CO_2, methane and CFCs (Houghton and Woodwell, 1989). Taken by themselves, however, the available data are difficult to interpret and some (Lindzen, 1990) have claimed that we must wait a few decades before definitive answers will be available. The present time is potentially a very important crossroad for humanity. Some caution is, however, warranted; even significant correlations among variables do not prove a common cause. On the other hand, if we do not react quickly enough, if we misinterpret or ignore "early warning" signals (ostrich syndrome), we may be faced with a situation that is totally beyond our control. This is the dilemma that must be faced by humanity at large, and, in particular, by political leaders in the developed world.

There has been a tendency for those involved in the study of climatic change to be concerned with the present and future (van Andel, 1989). The potential anthropogenic threat to the global environment is a unique phenomenon, but it can only be properly identified and interpreted against the background of past change. Past change is recorded in a number of different ways, but the only long-term record of climatic change is the stratigraphic record. The purpose of this paper is to present a brief review of some aspects of the ancient climatic record on Earth, with special emphasis on the geological evidence for previous glacial episodes.

SOME POSSIBLE CAUSES OF GLACIATION

Suggested causes of glaciation are much more numerous than the glaciations themselves. They can be divided into extra-terrestrial explanations and those in which a mechanism within the Earth itself is invoked. Extra-terrestrial mechanisms include proposed changes in solar radiation, passage of a dust cloud between Earth and sun, changes related to the galactic year (Steiner and Grillmair, 1973), shading of the Earth's equator by an icy ring similar to that of Saturn (Sheldon, 1984) and existence of, and changes in, orbital parameters (Milankovich effect). Terrestrial causes include explosive volcanism, which could produce a globe-encircling dust cloud screening the Earth from solar radiation (but could also cause increased atmospheric CO_2), and an anti-greenhouse effect due to decrease in atmospheric CO_2, caused either by formation of large amounts of carbonate rocks (Roberts, 1976; Schermerhorn, 1983) or decreased volcanic activity (Schermerhorn, 1983; Frakes, 1986). Work by Anderson (1982), Fischer (1984), Worsley *et al.* (1984), Nance *et al.* (1988) and Worsley and Nance (1989) led to the conclusion that low sea levels, related mainly to supercontinentality, could induce glaciation. Plate tectonic activity, involving movement of continents into polar latitudes, has been proposed (Crowell, 1978; Caputo and Crowell, 1985) and is well substantiated by the correspondence between glaciation and high paleolatitudes in Gondwanaland between the Devonian and Permo-Carboniferous (Veevers and Powell, 1987) mountain building. The importance of plate tectonic positioning of the continents as a control of oceanic circulation and heat distribution across the Earth's surface, was stressed by Ewing and Donn (1966). More recently, Broecker and Denton (1989) also attributed climatic fluctuations to changes in oceanic circulation. There is no reason why some of these mechanisms could not have acted in unison.

Following concepts developed by Sloss (1963) and Anderson (1982), Fischer (1984) suggested that Phanerozoic climatic history was largely controlled by a "supercycle" involving flooding and exposure of the continents to produce alternating "greenhouse" and "icehouse" conditions on a scale of about 400 million years (m.y.). Worsley *et al.* (1984), Nance *et al.* (1988) and Worsley and Nance (1989) proposed that the "supercycle" concept might also be applicable to the earlier part of geologic time. In this paper, that idea is explored further by looking at the nature of the geological evidence of glacial climates, particularly in the Precambrian. It is suggested that the prime cause of glaciation in Early and Late Proterozoic time and in the Late Paleozoic was the periodic assembly of much of the continental lithosphere into a supercontinent. Under such conditions, the continental crust has a blanketing effect on release of thermal energy from the Earth's interior (Nance *et al.*, 1988; Worsley and Nance, 1989). The supercontinent, therefore, becomes thermally buoyant (Anderson, 1982), leading to a global condition of low relative sea level. Subaerial exposure of such large areas of continental crust leads to enhanced weathering which, in turn, causes drawdown of large amounts of atmospheric CO_2. Up to 80% of the present drawdown of CO_2 is effected in this way (Houghton and Woodwell, 1989), the remainder being due to photosynthetic activity of plants. Reduction in atmospheric CO_2 would lead to diminution of the greenhouse effect and could result in the onset of glacial conditions (summers become sufficiently cool to permit a net annual accumulation of snow).

HISTORICAL EVIDENCE OF CLIMATIC CHANGE

Claims of anthropogenic greenhouse effect were made after the tragic dustbowl conditions in the United States in the 1930s, but the best documented record of global temperatures available (Hansen and Lebedeff, 1987) shows that subsequently, between 1940 and 1970, global temperatures dropped by about 0.2°C prior to the current upward trend. The reasons for such small-scale perturbations are not understood.

Looking further back into the historical record, there is also abundant evidence of significant climatic variation, notably the saga of the Westvikings (Gribbin and Gribbin, 1990). When the "Little Climatic Optimum" came to a close at the end of the 12th century, small bands of Norse settlers in Greenland (6-7,000 in number) found themselves in a deteriorating climatic regime that resulted in their isolation from Europe and eventually their total demise early in the 16th century. Historical records of these climatic variations have been confirmed by the study of oxygen isotopes in ice cores both in Greenland and Iceland and by tree ring studies (Delwaide and Payette, 1990). Again, the reasons for these cold centuries, from which the world is now emerging, are not known.

Evidence from Ice Cores

As mentioned above, studies of ice cores have yielded new and significant information concerning climatic variations in historical times. These results have also been extended into pre-history. The Vostok Antarctic core, produced as the result of a French-Soviet co-operation, has provided data for the last 160,000 years. Variations in deuterium content and $\delta^{18}O$ values from air bubbles trapped in the Antarctic ice have shown that, during the period represented by just over 2,000 m of ice accumulation, temperatures fluctuated by as much as 10°C (*see* Houghton and Woodwell, 1989, for a summary of the results). Such changes were anticipated, but the surprising aspects of this study were the concomitant variations in CO_2 and CH_4. The significance of these variations is not fully understood. For example, the inferred temperature fluctuations are much greater than would be expected from the CO_2 values obtained (Houghton and Woodwell, 1989). Also, the CO_2 values appear to coincide well with periods of deglaciation, but lag behind during the onset of glaciation. Whether glaciation brought about atmospheric variations or *vice versa* is not understood, but there appears to be a good correlation between the trace gas content and climate. According to Houghton and Woodwell (1989), photosynthetic activity is less sensitive to temperature change than rates of respiration and decay of plant material. They suggested that this might be one of the main reasons for the observed relationship between elevated temperatures and increased amounts of CO_2 and methane in air bubbles in the Vostok ice core. Elevated methane values might be the result of increased anaerobic decay rates associated with rising temperature. According to this model, the variations in atmospheric greenhouse gases would be an effect, rather than a cause, of global heating or cooling.

Similar studies of ice cores from the central part of the Asian continent, which is considered to be particularly sensitive to greenhouse warming (Lewin, 1989), show that this region is warmer now than at any other time since the Holocene maximum 6-8,000 years ago. The analysis of air trapped in ice cores thus provides a very sensitive measure of climatic events stretching back at least 160,000 years and potentially farther. Deep ice drilling is planned for Greenland and should yield equally interesting results.

Evidence from Ocean Sediment Cores: Support for the Milankovitch Theory

Changes in orbital parameters of the Earth, involving variations in the shape of the Earth's orbit around the sun, precession of the equinoxes and changes in the tilt of the Earth's spin axis (obliquity of the ecliptic), are generally known collectively as the Milankovitch effect after the Yugoslav mathematician. Some aspects of these theories were, however, known in the middle of the 19th century, due to the work of James Croll, a self-educated Scot, and J.A. Adhemar, the French mathematician. For a long time, most earth scientists considered the question of orbital parameters to be an interesting, but esoteric, astronomical theory. With the development of isotopic investigations of foraminiferal remains from deep ocean cores, however, and the discovery of coincidence between perceived major climatic fluctuations and the predicted periodicities of glacial advance-retreat cycles, the theory entered a period of respectability (*e.g.*, Hays *et al.*, 1976) and is now widely, though not universally (Kunzig, 1989) nor totally (Broecker and Denton, 1989, 1990), accepted as the main regulating mechanism responsible for advance-retreat cycles during the Pleistocene Ice Age.

It is likely that Milankovitch forcing has existed for much of geologic history (Herbert and Fischer, 1986; Berger and Loutre, 1989). The absence of any evidence of glaciation throughout long periods of geologic time (Figure 1), however, suggests that it is not the prime cause of glaciation, but may rather modulate the behaviour of ice sheets, formed in response to some other mechanism.

Evidence from the Rock Record

The only long-term paleoclimatic record is the geologic record. It is imperfect and incomplete. In this paper, attention is focussed on one aspect of paleoclimate — the evidence of glaciation. Glacial deposits are readily identified. Features such as striated pavements and clasts, dropstones and widespread diamictites are easy to recognize. Together with numerous other more subtle criteria, such as major element geochemical studies (Nesbitt and Young, 1982), they provide unequivocal evidence of glacial climate. It has been argued (Schermerhorn, 1974) that many Late Proterozoic sequences, interpreted as glaciogenic, were formed as a result of a special tectonic setting, with active down-to-basin faulting triggering mass flows and producing diamictons, which resemble those formed under glacial conditions. Numerous subsequent studies (*see* Hambrey and Harland, 1981, for individual case histories) have shown that Schermerhorn's inference of an active rift setting for many of these basins was correct, but that most also contain evidence of glacial influence.

The Archean record. According to the geologic record, *major* glaciation has occurred only four times during the almost four billion years of Earth history for which we have a preserved record (Figure 1). One of the most striking aspects of the record is the near-complete absence of evidence of glaciation during the first half of geologic history. Possible glacial deposits are present in the Witwatersrand succession of southern Africa (Harland, 1981) and there is local evidence of glacial transport in Archean rocks associated with the Stillwater Complex in Montana (Page, 1981). The record is otherwise barren.

Interpretation: Was the early Earth warm? The dearth of glaciogenic rocks in the Archean is surprising because it is widely believed (Sagan and Mullen, 1972; Kasting, 1987, 1989; Gough, 1981; Kasting and Toon, 1989; Gilliland, 1989) that during the early part of the Earth's history, the radiative power of the sun was only about 70% of its present value. The drop in surface temperature, given a primitive atmosphere with concentrations of greenhouse gases comparable to those of the present atmosphere, would have been more than 30°C (Kasting *et al.*, 1984). The presence of abundant waterlain Archean sedimentary rocks and the dearth of glaciogenic deposits clearly indicate that the early Earth was not frozen. This has been called the faint young sun problem or paradox (Kasting, 1987). The simplest resolution of the paradox is to invoke an enhanced greenhouse effect during the early part of Earth history. Sagan and Mullen (1972) suggested ammonia as the greenhouse gas, but others (*e.g.*, Kasting, 1982) showed that ammonia is subject to photochemical dissociation. Hart (1978) proposed that CO_2, which is much more stable (in the presence of trace amounts of water vapour), was a more likely greenhouse gas. As pointed out by Kasting (1979), there is no shortage of terrestrial CO_2. Vast amounts of CO_2 (equivalent to about 60 bars) are currently trapped in carbonate rocks. Other gases, such as methane and related hydrocarbons, could also have contributed to greenhouse warming. Thus, in spite of the proposed early faint sun, geological evidence supports the notion that the

Archean Earth remained almost free of glacial ice. The absence of extensive Archean cratons may also have been a factor both in preventing drawdown of CO_2 by weathering and in inhibiting development of continental glaciers.

The Early Proterozoic record. The Early Proterozoic record (Figure 1) includes the first convincing evidence of widespread glaciation. Glaciogenic deposits are reported from North America, Finland, South Africa, Australia and possibly India. Those of North America are the thickest and most widespread. Perhaps the best known is the Gowganda Formation, which forms part of the Huronian Supergroup (2500-2100 Ma) on the north shore of Lake Huron. Glacial deposits also form part of a remarkably similar Early Proterozoic stratigraphic sequence in southeastern Wyoming, the Snowy Pass Supergroup (Houston *et al.*, 1981). In the Northwest Territories on the west side of Hudson Bay, part of the Hurwitz Group (Bell, 1970) consists of glaciogenic diamictites (Young, 1973; Young and McLennan, 1981). In all of these areas, it has been suggested (Young, 1975; Young, 1983; Young, 1987; Zolnia *et al.*, 1984; Young and Nesbitt, 1985; Karlstrom *et al.*, 1983) that the glacial sediments were preserved during a period of continental rifting. In areas where a thick stratigraphic succession is preserved, there is evidence of several glacial episodes, separated by periods of intense chemical weathering. The tectonic setting of locally preserved Early Proterozoic glaciogenic rocks in Australia and South Africa is much less clearly understood, but it has been suggested (Young, 1989) that they might have formed in response to mountain building associated with ocean closure.

Repeated Early Proterozoic glaciation as the result of negative feedback. The Early Proterozoic stratigraphic record in each of the major North American outcrop areas includes evidence of several glacial episodes. In the Huronian Supergroup (Figure 2), for example, there are three glaciogenic formations: the Ramsay Lake, Bruce and Gowganda formations (Frarey and Roscoe, 1970). These glaciogenic formations are interbedded with mudstones and sandstones that contain evidence of intense chemical weathering (Chandler *et al.*, 1969; Young, 1973; Nesbitt and Young, 1982). The association between glaciogenic and highly weathered rocks is puzzling, although the time periods separating deposition of these contrasting rock types are not known. Deposition of the entire supergroup is loosely bracketed between about 2500 Ma and 2100 Ma. Although the time scale of these climatic fluctuations is poorly constrained, it appears much too great to be due to the Milankovitch Effect. They are here attributed to a negative feedback mechanism. Weathering of newly emergent continents (Taylor and McLennan, 1985), resulting in removal of atmospheric CO_2, would have been greatly enhanced during periods of lowered sea level. This could have caused initiation of a glaciation. With widespread development of glaciation, however, there would be a negative feedback mechanism, reducing the efficacy of the weathering process. As the glaciers expanded, ice-covered regions would no longer have been available for chemical weathering. General lowering of global temperatures would also cause a slowdown of weathering rates. Reduced weathering areas and rates would eventually lead to a build-up of atmospheric CO_2 and re-establishment of a warm climatic regime. This alternation of contrasted climatic regimes would continue until the supercontinent began to break up and sea level rose. Flooding of the continental crust would lead to a significant decrease in chemical weathering, causing a build up of CO_2 and ushering in a new period of warm global climate. This feedback machanism is proposed as an explanation for the alternation of glacial episodes and periods of intense chemical weathering in many Early Proterozoic successions.

If the CO_2 content of the Early Proterozoic atmosphere were much higher than today, as has been suggested on both theoretical grounds (Hart, 1978; Kasting, 1989) and on the basis of geological observations (Young, 1973; Harland and Herod, 1975; Schermerhorn, 1983; Reimer, 1986), and if the faint young sun theory is correct, then lower average global temperatures (and the onset of glacial conditions) may have been possible at much higher partial pressures of CO_2.

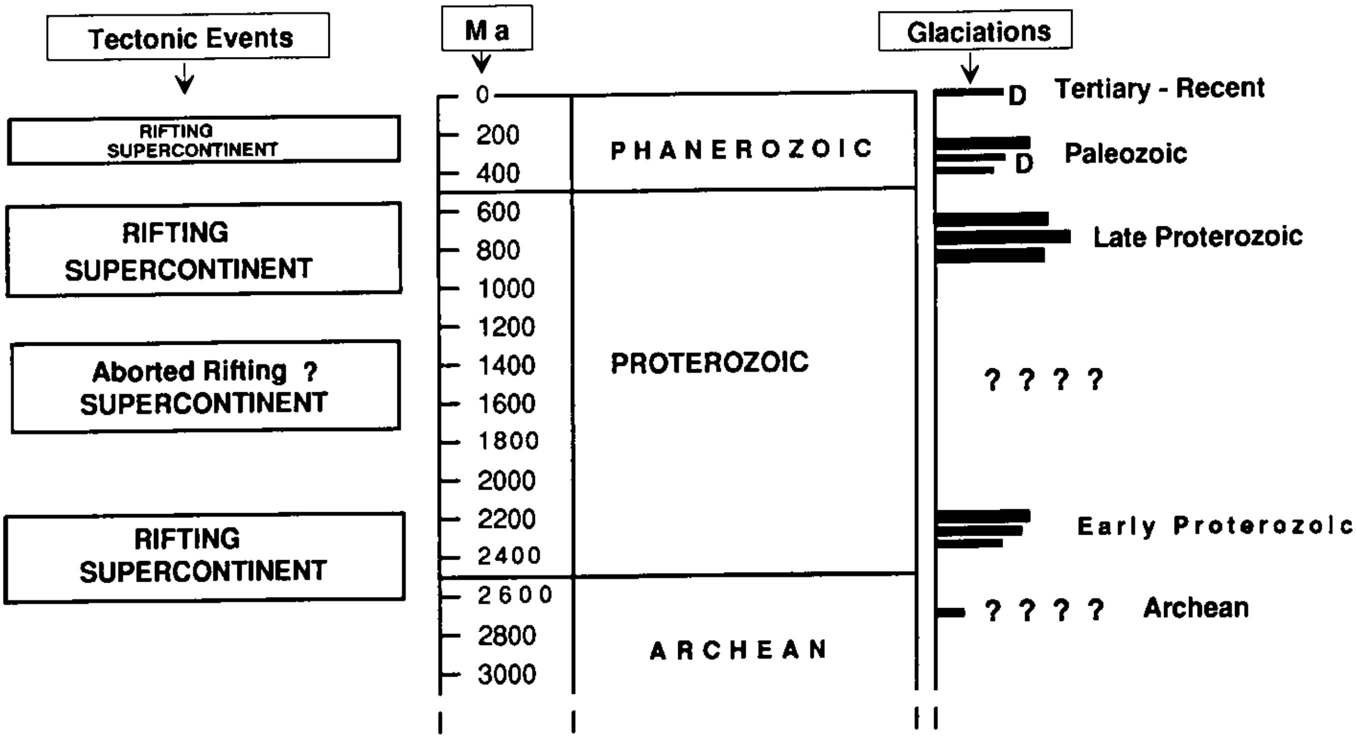

Figure 1 *Time distribution of glaciogenic sedimentary rocks to show their sporadic nature and possible relationship with periods of supercontinentality. Exceptions, shown by the letter D on figure, are the Tertiary-Recent and possibly the Ordovician and Devonian, which may be related to periods of continental dispersal and mature "Atlantic-style" oceans. See text for explanation.*

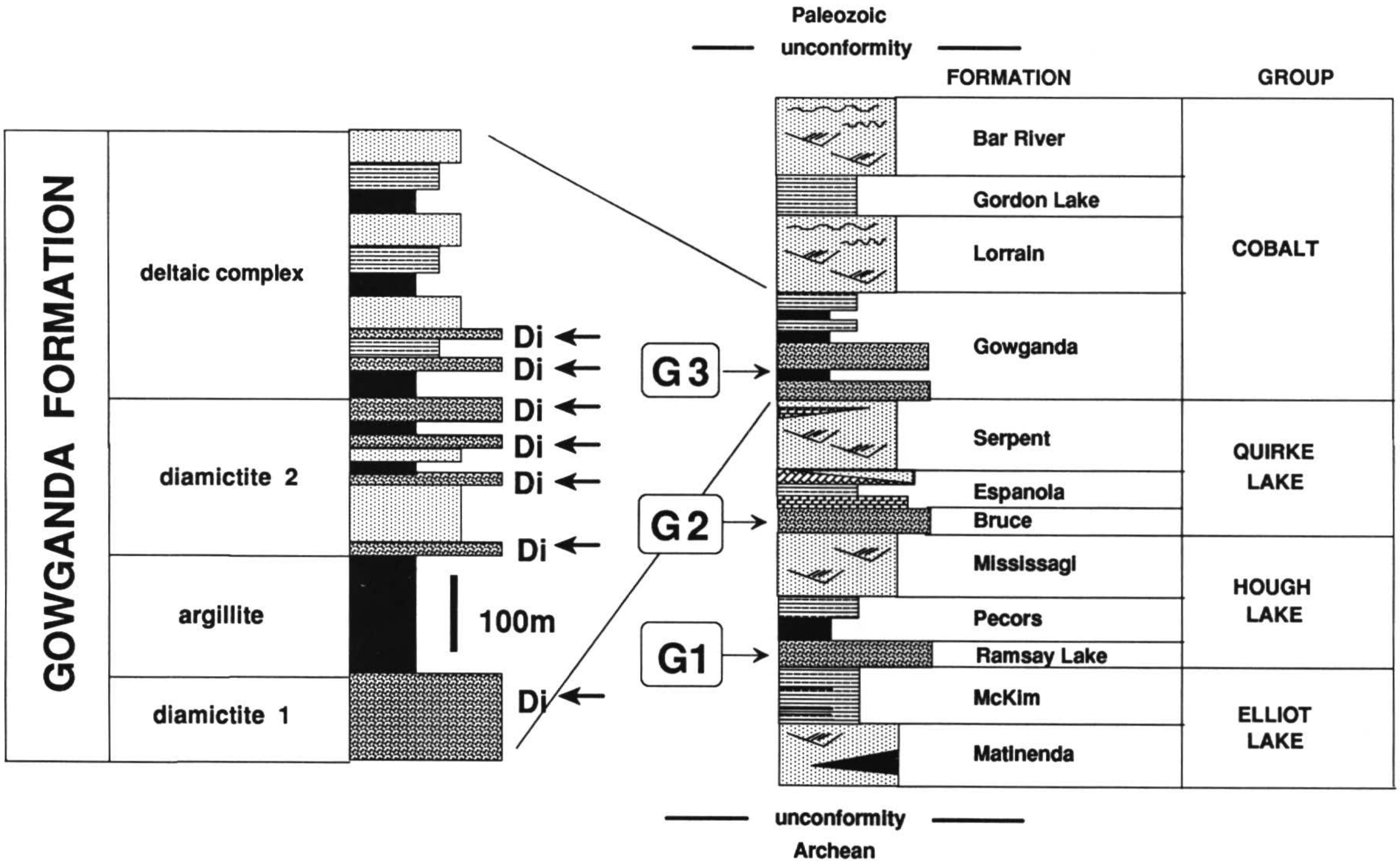

Figure 2 *Schematic representation of the stratigraphy of the Huronian Supergroup (about 10 km thick) on the north shore of Lake Huron. Note three glacial episodes, G1-G3. Many of the intervening formations show evidence of strong weathering. Column at left shows a schematic representation of the stratigraphy of the Gowganda Formation in the southern part of the Huronian outcrop belt. Note that the central part of the formation contains several diamictites, indicated by* ***Di****, representing smaller scale phenomena (Milankovitch cycles?) than those of the "G" events shown at right.*

Under such conditions, the postulated climatic changes would have been much more rapidly accomplished and dramatic than in subsequent geologic times.

The mid-Proterozoic gap. Between the time of Huronian deposition and the onset of the Late Proterozoic glaciations, there is a long period (about 1000 m.y.) when there is no convincing evidence of glaciation on the planet (Figure 1). According to Hoffman (1989), the period from about 2000 Ma to 1800 Ma was a time of aggregation of several microcontinents in the Canadian-Baltic shield. Several authors (Windley, 1984; Piper, 1978; Hoffman, 1989) have proposed the existence of a supercontinent during the ensuing period of geological history. According to the theory outlined above, such a configuration should have been particularly propitious for glaciation. Hoffman (1989) suggested that the mid-Proterozoic supercontinent was subjected to abortive attempts at fragmentation as evidenced by unusually widespread intrusive and extrusive mafic and acid magmatism (including anorthosites and rapakivi granites) from about 1800 Ma to 1300 Ma. These events may indicate a unique stage in the thermal evolution of the Earth, involving interaction between the first(?) extensive supercontinent and high mantle temperatures. Outgassing of CO_2 related to voluminous continental magmatism may have been sufficient to balance the predicted large drawdown by weathering.

The Late Proterozoic record. Late Proterozoic glaciogenic rocks are known from all the continents. They provide evidence of a very widespread and long-ranging glacial episode (or episodes), possibly with three peaks (Williams, 1975), in the period between about 900 Ma and the Cambrian. Striking thickness and facies changes across contemporaneous faults have led to the conclusion that many Late Proterozoic glaciogenic successions formed in a rift setting (Schermerhorn, 1974; Coats, 1981; Preiss, 1987; Young and Gostin, 1989; Yeo, 1981; Eisbacher, 1985). This interpretation has been strengthened recently by the interpretation of associated iron- and manganese-rich sedimentary units as products of hydrothermal activity (Yeo, 1981; Breitkopf, 1988). It has been proposed, for example in the North American Cordillera (Bond *et al.*, 1984) and in Australia (Lindsey *et al.*, 1987), that breakup did not occur until the Cambrian, so that the rift episode may have extended from about 700 Ma (Jefferson and Parrish, 1989) to the beginning of the Cambrian. The reason for this protracted rift episode is not understood.

The deepest freeze? — Tropical glaciation in the Late Proterozoic? Harland (1964) suggested that the wide distribution of Late Proterozoic glaciogenic deposits might signify a glaciation of global dimensions. This hypothesis was supported by the earlier paleomagnetic studies of Harland and Bidgood (1959) and Bidgood and Harland (1961), which led to the proposal that some of the Late Proterozoic glaciogenic rocks formed at low paleolatitudes. This suggestion gained credence because of the common association of Late Proterozoic diamictites with dolostones, red beds, iron formations and other facies thought to be indicative of warm climates. In some areas, such as the northern part of the North American Cordillera (Yeo, 1981; Young, 1982) and in Namibia (Breitkopf, 1988), "red beds" and iron formations are now thought to be products of hydrothermal activity and therefore cannot be construed as evidence of anomalous climatic conditions associated with Late Proterozoic glaciation. On the other hand, the intimate association with dolostones of "primary" or early diagenetic origin appears to be anomalous. There have been numerous attempts to explain these apparently contradictory facies associations. Spencer (1971) proposed that the Port Askaig Tillite of western Scotland and other Late Proterozoic glacial deposits of the North Atlantic region were produced by a vast icecap that developed in equatorial latitudes. This interpretation has been broadly followed by Fairchild and Hambrey (1984), who inferred that, in the Late Proterozoic of northeastern Svalbard, glacial conditions were introduced from time to time into an otherwise warm climatic regime.

In an attempt to resolve these apparent climatological enigmas, Williams (1975) proposed that the obliquity of the ecliptic varied throughout geologic time. During periods of greatly increased obliquity (54°), insolation should be greater in polar than in equatorial latitudes, so that the equatorial belt would be preferentially glaciated. Williams (1975) also postulated increased effects of seasonality.

Using the analogy of the Permo-Carboniferous glaciation of Gondwanaland, Crowell (1983) suggested that the Late Proterozoic was a period of rapid plate tectonic movement and that continents were sequentially glaciated in polar latitudes, but did not receive a paleomagnetic signature until later, when they moved to lower paleolatitudes. Others (Stupavsky *et al.*, 1982) claimed that earlier paleomagnetic results, such as those reported by Tarling (1974), were spurious and due to later magnetic overprinting. More recent results (Embleton and Williams, 1986) and reviews (Chumakov and Elston, 1989), however, have lent considerable support to the idea that most of the continents were in low paleolatitudes throughout most of the Middle and Late Proterozoic. Both paleomagnetic data (Piper, 1978; Khramov, 1983; Chumakov and Elston, 1989) and geological arguments (Windley, 1977; Hoffman, 1989) also favour the idea of a supercontinent throughout much of Middle to Late Precambrian time.

Using the arguments presented above, such a supercontinent would likely be high-standing and therefore subject to considerable chemical weathering. High rainfall and elevated temperatures in the proposed equatorial setting would have further enhanced weathering rates, resulting in significant drawdown of atmospheric CO_2 and, eventually, global cooling. With the continents strung out in a unified mass along the equator (Khramov, 1983), glaciation could not have occurred in polar regions. Instead, the polar seas would have frozen and the zone of sea ice would have gradually encroached on lower latitudes. Eventually, build up of glaciers could have taken place in low latitudes, presumably initially at high altitudes (Schermerhorn, 1983). Some parts of the low-latitude oceans must have remained ice-free, at least during the build up of ice on the continents, to maintain a supply of moisture. When glaciation became so widespread and temperatures so low that weathering was significantly inhibited, CO_2 would have started to build up in the atmosphere again, eventually causing disintegration of the ice sheets and re-establishment of a "normal" warm climatic regime in tropical latitudes. This condition would prevail until another glaciation was induced by depletion of atmospheric CO_2 by weathering. Thus, a built-in negative feedback mechanism could have resulted in alternation of glacial and warm climatic conditions until the cycle was broken by continental fragmentation and flooding of the continental interiors (Worsley *et al.*, 1984; Fischer, 1984), ushering in a long period dominated by warm paleoclimates. This interpretation is in keeping with much of the stratigraphic record of the Late Proterozoic, which appears to involve periodic incursion of glacial episodes in an otherwise warm climatic period. Smaller scale oscillations, such as those recorded by the many glacial advances during deposition of the Late Proterozoic Port Askaig Tillite of western Scotland (Spencer, 1971), may be attributable to Milankovitch forcing, as suggested by Hambrey (1983).

Harland and Herod (1975) also suggested that Early and Late Proterozoic glaciation took place due to the drawdown of atmospheric CO_2, but they invoked photosynthesis, rather than chemical weathering, as the main mechanism. Even with the present extensive plant cover on the continents, however, it is believed (Worsley *et al.*, 1984; Houghton and Woodwell, 1989) that weathering processes account for about 80% of CO_2 removal from the atmosphere. Schermerhorn (1983) also deduced from the abundance of carbonates and dearth of volcanic activity that the Late Proterozoic atmosphere was depleted in CO_2 and that tectonically elevated source areas could have shed glaciers into tropical seas.

The Phanerozoic record. Evidence of glaciation in the Late Ordovician is abundant in North Africa (Deynoux and Trompette, 1981; Biju-Duval *et al.*, 1981) and, to a lesser degree, in South Africa, South America, Europe and eastern North America. There is local evidence of Late Devonian glaciation in Brazil (Caputo and Crowell, 1985), but by far the most extensive and well-known glaciation of the Paleozoic is that of the Permo-Carboniferous. This glaciation is well represented in the southern hemisphere (Crowell, 1982). The presence of scattered Permo-Carboniferous glacial deposits and evidence from directional structures suggesting that some of the glaciers had apparently come from an oceanward direction were among the lines of evidence used by early proponents of the hypothesis of continental drift. It is now widely accepted that the southern continents were formerly joined together to form Gondwanaland. There appears to be some correlation between the successive events of the Permo-Carboniferous glaciation and the movement of Gondwanaland across the south polar region (Crowell, 1978).

The Phanerozoic high-latitude glaciations. According to Smith *et al.* (1981), the northern continents were widely scattered during Late Ordovician time, but the Gondwana supercontinent was in existence, and north Africa, where the most spectacular evidence of Late Ordovician glaciation is preserved (Deynoux and Trompette, 1981), was situated over the South Pole.

The timing and distribution of glaciation during the Devonian and Permo-Carboniferous periods have been well documented in papers by Crowell (1978), Caputo and Crowell (1985) and Veevers and Powell (1987). The main cause cited for these glaciations was also the location of continental areas over the South Pole. Crowell (1978) and Caputo and Crowell (1985) showed how the sequential passage of what are now the southern continents across the south polar region was related to glaciation in the Late Devonian and Permo-Carboniferous. This glaciation lasted from about 360 Ma to about 255 Ma (Veevers and Powell, 1987) when Gondwanaland began to drift away from the South Pole (Smith and Briden, 1977; Smith *et al.*, 1981). It is suggested that two main factors may have contributed to the Late Paleozoic glaciation: low global temperatures as a result of an anti-greenhouse effect caused by weathering due to the emergent state of the supercontinent, and positioning of part of the supercontinent at high paleolatitudes. Glaciation appears to have terminated in the Late Permian due to the movement of Gondwanaland away from the polar zone, suggesting that latitudinal position was the more important factor at that time. Throughout the Triassic, the supercontinent was not located over the poles. In the Early Jurassic, about 180 m.y., breakup of the supercontinent was initiated, with concomitant sea-level rise and global warming.

The Cenozoic record. About 80 m.y. ago, in the Late Cretaceous, the combined effect of Antarctica (together with Australia) drifting back into polar latitudes and the lowering of sea level due to the maturing (foundering) Atlantic sea floor (Worsley *et al.*, 1984) brought about a cooling phase that culminated in initiation of glaciation in Antarctica about 36 m.y. ago (Barrett, 1981). Perhaps because of the lack of a suitable continental region at the North Pole, or because of the nature of oceanic circulation there, the cooling phase was expressed much later in the northern hemisphere when continental glaciers first extended down to mid-latitudes about 3 m.y. ago.

DISCUSSION

Glaciations, like most natural phenomena, do not have a single simple cause, but are probably the result of a complex interplay of conditions on the surface of the planet. A summary of the major glaciations and possible causative factors is given in Table 1. In this brief review, an attempt has been made to interpret some of the evidence from the geological record. The dearth of Archean glacial deposits is attributed to high CO_2 levels in the atmosphere and a lack of extensive continental crust. Early Proterozoic glaciation saw the first widespread development of glaciogenic rocks. The main cause of glaciation was the combination of the still-faint sun and lowered atmospheric CO_2 levels due to weathering of the first elevated

Table 1 **Distribution in space and time of major glacial episodes preserved in the geologic record, together with suggested causes.**

ICE AGE	Early Proterozoic	Late Proterozoic	Late Paleozoic	Cenozoic
Solar Radiation	————	———— increasing ————	————	————→
p_{CO_2}	————	———— decreasing ————	————	————→
Continental Crust	Emergent cratons	Emergent equatorial(?) supercontinent	Supercontinent (Laurasia)	Scattered emergent continents
Location	N. America W. Australia S. Africa India	Global low latitudes?	High latitudes Gondwanaland	High latitudes Antarctica Greenland N. Europe N. Asia N. America S. America
First-order Cause	Faint sun CO_2 depletion by weathering	CO_2 depletion by equatorial weathering	Polar situation of part of supercontinent CO_2 depletion by weathering	Polar situation of some continents CO_2 depletion due to emergent continents (mature Atlantic Ocean)
Other Features	Multiple glaciation due to negative feedback mechanism under high p_{CO_2} Milankovitch cycles?	Multiple glaciation due to negative feedback mechanism Milankovitch cycles?	Sequential glaciation as different areas move into polar latitudes Milankovitch cycles?	Initiated in Antarctic about 36 m.y. ago; in Arctic, about 3 m.y. ago Milankovitch cycles Little Ice Age cycles Anthropogenic warming?

extensive continental crust. Support for this interpretation comes from the interbedding of glaciogenic formations and highly weathered units; glaciation took place under conditions of relatively high p_{CO_2} so that the withdrawal of glacial ice permitted the rapid onset of rock weathering. This cycle was broken when fragmentation of the supercontinent took place.

In spite of the proposed existence of a supercontinent throughout much of the Middle Proterozoic, from about 2000 Ma to 1000 Ma, there is no convincing evidence of glaciation. One possible explanation is that this was a period of continental accretion, followed by largely aborted attempts at rifting (Hoffman, 1989). These events produced magmatic activity on a massive scale, here postulated to have kept atmospheric CO_2 at sufficiently high levels to maintain a warm equable global climate.

The geologic record suggests that the Late Proterozoic saw the greatest proliferation of icecaps the world has ever experienced. A growing body of paleomagnetic data suggests that many (if not most) Late Proterozoic glaciogenic rocks formed at low paleolatitudes. Geological studies provide evidence of a rift-type environment for these deposits in many parts of the world. From these data, it is inferred that much of the continental crust was in the form of an elongate supercontinent (Piper, 1978) located mainly in equatorial latitudes. Using the analogue of Phanerozoic glaciations, this seems to be a most unlikely scenario for widespread glaciation. Location of the majority of continents in low latitudes would, however, have led to massive drawdown of atmospheric CO_2, with consequent cooling, initially in the polar oceans, but eventually spreading to the continental mass. In spite of increased albedo, gradual buildup of atmospheric CO_2 (the negative feedback mechanism) would eventually have caused the glaciers to disappear, with reversion to a warm climatic regime because of the tropical location. Such an alternation of glacial and warm conditions would have continued until the cycle was broken at the time of continental fragmentation in the latest Proterozoic-Early Cambrian. This mechanism provides an explanation for the low paleolatitudes, the multiple glaciations and the interbedding of warm climatic indicators (dolomite, *etc.*) with glaciogenic formations. If this interpretation is correct, then the Late Proterozoic glacial periods may have been the coldest the Earth has ever experienced.

Attempts to interpret Phanerozoic glacial episodes are much more closely constrained. For the first time, there is paleontological control and there are reliable paleomagnetic reconstructions. All of the Phanerozoic glaciations appear to have taken place on continents in high latitudes and, given the much-reduced CO_2 content of the atmosphere, this may have been the major paleoclimatic control. It is interesting, however, to note that there is also some correspondence between periods of lowered sea level (inferred from plate tectonic configurations) and glaciations. The Permo-Carboniferous Gondwana glaciation took place in south polar latitudes, but part of the reason for lowered global temperatures may have been further reduction of atmospheric CO_2 by weathering of the high-standing Laurasian part of the Pangean supercontinent. Likewise, the Cenozoic-Recent glaciation (and possibly the Late Ordovician glaciation) affected areas in polar latitudes (or paleolatitudes), but under conditions of lowered sea level, related not to the existence of a supercontinent, but rather to the presence of wide mature "Atlantic-style" oceans which would also contribute to a lowering of global sea levels.

THE FUTURE

At first glance, these speculations on glacial history may seem esoteric and of no immediate relevance to mankind. They do, however, provide a framework within which the interpretation and prediction of smaller scale climatic variations can be better understood.

The major problem in making predictions about climatic change is the scale of the record. For example, measurement of variation in daily average air temperature at one location, say in mid-latitudes in the northern hemisphere from July to December, would lead to prediction of a cooling trend. If the same procedure were carried out at the same place from December to July, the prediction would be that warming was in store. Measurements spanning several years would reveal that both predictions were wrong; an oscillatory pattern would emerge, but no linear trend. Since it was realized that atmospheric CO_2 is on the rise, there has been a concerted effort to gather data, from as long a time period as possible, concerning average global temperatures, usually air and water temperatures. These data are largely of an historic nature and are correspondingly flawed, but the analysis of the data suggests that the Earth has warmed about 0.6°C over the last century or so. Thus, the immediate concern is the possibility of anthropogenic modification of the global environment, mainly through addition of greenhouse gases to the atmosphere. The fear is that

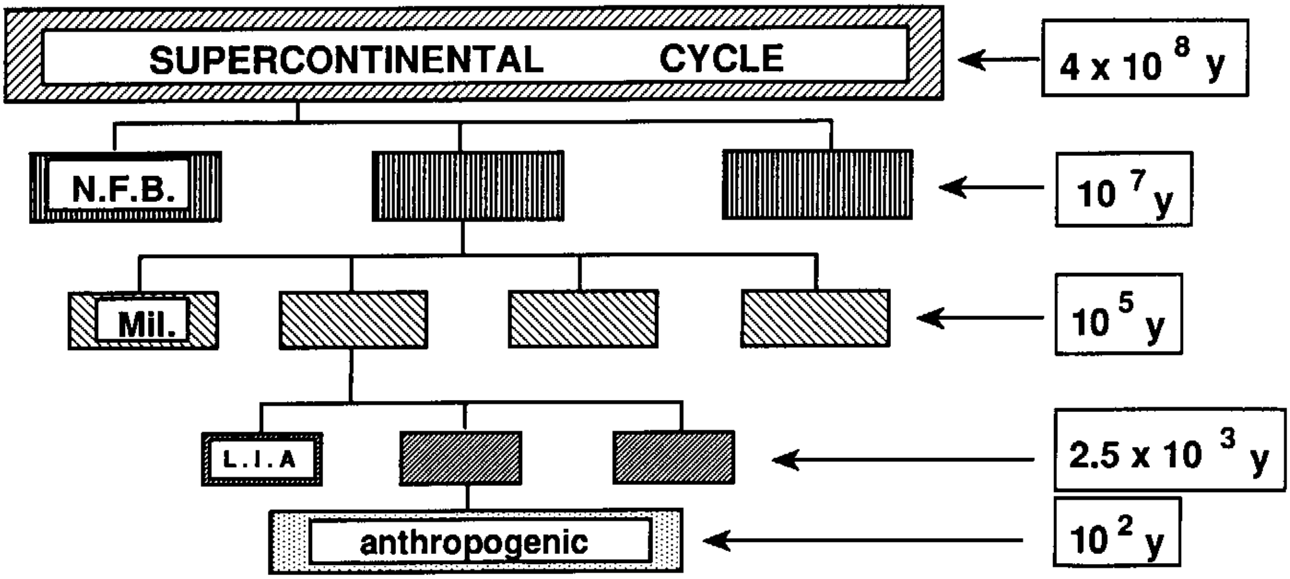

Figure 3 *Suggested hierarchical ranking of some of the phenomena thought to have influenced climatic conditions on Earth.* ***N.F.B.****, negative feedback mechanism used to explain multiple glaciation in both Early and Late Proterozoic sequences;* ***Mil.****, Milankovitch Effect, related to orbital parameters of the Earth;* ***L.I.A.****, "Little Ice Age" cycle. Figures at right indicate the approximate duration of time (years) involved in each process. See text for discussion.*

these effects will be very rapid and may lead, among other things, to rising global temperatures, elevated sea levels and aridity in previously fertile regions. Apart from the potential anthropogenic influence, what are the nature and timing of predictions based on interpretations of the geologic record? According to Milankovitch theory, the Earth should be entering a new ice age (Mitchell, 1977; Imbrie and Imbrie, 1980). The Pleistocene marine record (Hays *et al.*, 1976) suggests that interglacial warm periods, like the present, are relatively short (about 10,000-12,000 years). Since the present interglacial began about 10,000 years ago, one might predict that the descent into glacial conditions is imminent. Indeed, a gradual decrease in global temperatures, about 2°C since the climatic optimum about 7000 years ago, has been suggested (Imbrie and Imbrie, 1979, p. 179). Superimposed on this gradual decline is a poorly understood, smaller scale climatic oscillation on the order of 2500 years (Denton and Karlen, 1973). According to the past record of this small-scale cycle, the Earth should be on a short-term warming trend as it comes out of the Little Ice Age. This trend should continue for about 1000 years, when it should give way to a cooling trend. The small-scale cooling trend would then be acting in phase with the Milankovitch effect and the Earth should enter a cold period, achieving maximum glacial cover about 23,000 years from now. Some of the factors that might contribute to climatic change, together with estimated time scales, are shown in Figure 3.

Is the Earth destined to remain permanently in the grip of the Cenozoic-Recent ice age? The sporadic nature of glaciation in the geologic past and the proposed plate tectonic control suggest that it will not. It can be inferred that glaciation should end when subduction begins around the Atlantic margins. Subduction of the old, cold, dense oceanic crust on the Atlantic margins and initiation of ocean closure should lead to extensive continental flooding as the proportion of young oceanic crust increases. This would result in decreased continental weathering and increased atmospheric CO_2, and would potentially usher in a new period of high sea levels and warm climate, comparable to the Cretaceous. Such a prediction is on a scale of millions of years. These and other predictions on a large time scale (*see* Worsley and Nance, 1989) may be of little immediate concern, but, if we have a serious commitment to the long-term survival of our species on this planet, they should be part of our arsenal of knowledge. Such knowledge can only be derived from study of the geologic record.

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