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The evidence and implications of polar ice during the Mesozoic

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Abstract

The Mesozoic, perhaps representing the longest period of warmth during Phanerozoic Earth history, contains in general sparse and frequently equivocal evidence for polar ice. Although this time is undoubtedly punctuated by oscillations in climate, whether sufficient to lead to polar cooling and the formation of polar ice (an inviting mechanism to account for faunal and floral distribution patterns and large scale sea level change), has been widely debated. Mesozoic evidence for glacial conditions includes abraded rock surfaces, generally unsorted stone-rich beds and the presence of dropstones rafted by ice within a finer-grained host sediment. Faunal and floral evidence has also been utilised to determine the presence or absence of cold or sub-freezing polar conditions, together with more indirect evidence for glacial conditions derived from General Circulation Model (GCM) simulations of climate, the analysis of clay mineral distributions, glendonite abundance, and palaeontological and sedimentological evidence for globally synchronous sea level change. The extent of possible glacial environments during the Mesozoic has been established by plotting published reports of glacial sediments on palaeogeographic reconstructions. The general clustering of evidence at high palaeolatitudes suggests that the extent of polar ice during the Mesozoic is likely to have been approximately one third the size of the present day. Based on such evidence a number of episodes of cold or sub-freezing polar climates during the Bajocian–Bathonian, Tithonian/Volgian, Valanginian and Aptian are recognised. Evidence exists possibly also for a cold episode during the early Jurassic (?Pliensbachian) although poorly constrained owing to limited biostratigraphical control. The longevity of these events may be represented by a ‘cold snap’ within a stage, although undoubtedly the possible ‘smearing’ of ages may have had the effect of lengthening and hence promoting the importance of these proposed events. The climate regime of the Earth during these times may be hypothesised to be characterised by a relatively steep pole-to-equator temperature gradient where low-latitude regions are as warm or warmer than today. The evidence to support such reasoning includes sharp increases in the areal distribution of both glendonites and deposits with affinities to glacial tillites and dropstones for these times. Coincidental falls of sea level, arid events and an increased bipolarity of faunas at these times imparts further confidence that these events were of a magnitude to effect the Earth as a whole.

Keywords: polar ice; Mesozoic; glacial conditions

1. Introduction

The Earth has a long glacial history, extending from the Present back into the Archean. The Mesozoic perhaps represents the longest period of warmth during Phanerozoic history and although undoubtedly punctuated by oscillations of climate, whether these are sufficient to lead to cooling and the formation of polar ice has been widely debated (e.g., Barron, 1983; Kemper, 1987; Crowley and North,

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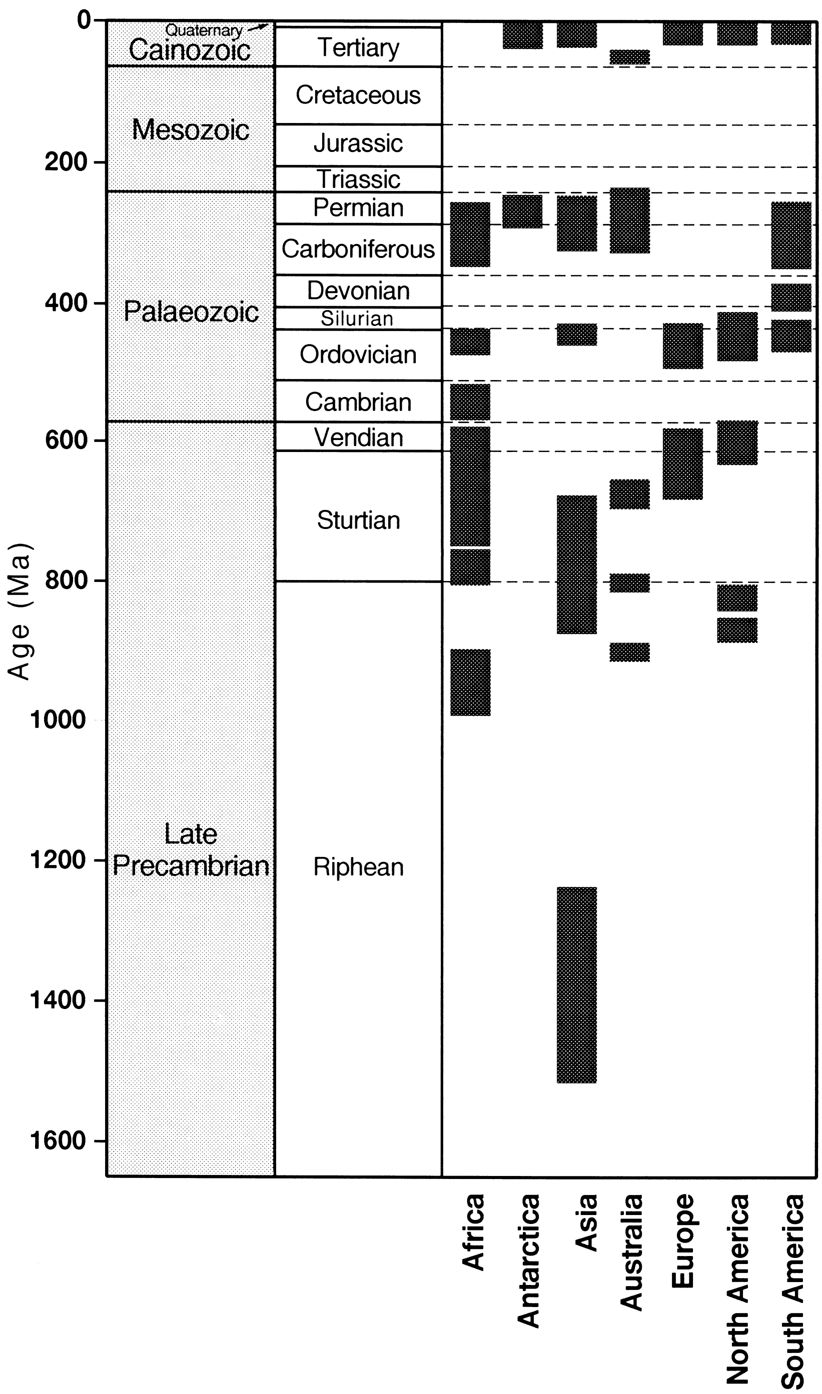

Fig. 1. The Earth's glacial record from the late Precambrian to Cainozoic. Modified from Eyles and Eyles (1992) from data principally compiled by Hambrey and Harland (1981).

1991; Frakes et al., 1992; Hallam, 1993; Chumakov, 1995; Bennett and Doyle, 1996; Frakes, 1999; Oyarzun et al., 1999). Glacial sediments of Precambrian and Palaeozoic age are recognised and it is not until the latest Eocene–earliest Oligocene that significant amounts of polar ice (on East Antarctica) are accepted (e.g., Kennett, 1977; Dingle and Lavelle, 1998). Hence, a possible gap exists in the glacial record (Fig. 1). Studies which have assessed the evidence for ice during the Mesozoic (e.g., Epshteyn, 1978; Kaplan, 1978; Kemper, 1987; Frakes and Francis, 1988; Frakes et al., 1992, 1995; Eyles, 1993; Chumakov and Frakes, 1997) have found that although direct indications are sparse and often equivocal, evidence for ice nonetheless exists. In contrast, some recent studies (e.g., Rowley and Markwick, 1992; Hallam, 1993; Bennett and Doyle, 1996; Markwick and Rowley, 1998) have found little evidence for ice and suggested its presence is based solely upon inference or wishful thinking only.

The climate of the Mesozoic has also been intensively studied from a General Circulation Model (GCM) viewpoint (e.g., Kutzbach and Gallimore, 1989; Chandler et al., 1992; Moore et al., 1992; Barron et al., 1993, 1995; Fawcett et al., 1994; Wilson et al., 1994; Price et al., 1995; Valdes et al., 1995). In simulations of global Jurassic and Cretaceous climate by Barron and Washington (1982), Sloan and Barron (1990) and Moore et al. (1992), high-latitude regions develop cold temperatures which provide adequate leeway to argue for the presence or absence of high-latitude ice. More recent simulations of the mid-Cretaceous by Barron et al. (1993; 1995) and Valdes et al. (1996) have, however, demonstrated that a combination of increased CO_2 in concert with changes in the oceanic heat transport resulted in significant polar warming, reducing the likelihood of high-latitude ice. A number of other investigations (e.g., Weissert and Lini, 1991; Sellwood et al., 1994; Stoll and Schrag, 1996; Constantine et al., 1998) have, however, also gone some way in casting doubt upon the longevity of continuous warmth during this time.

The frequently equivocal nature of evidence for Mesozoic ice may in part stem from the disparate and often obscure sources of information and from the inherently poorly dated nature of possible glacial features and sediments. The aims of this study are therefore to draw together this information in order to review the key issues with respect to understanding and verifying the evidence for ice during the Mesozoic. The theoretical need to invoke the presence of polar ice, which is often seen as an inviting mechanism to account for faunal and floral distribution patterns and large-scale sea level change, will be addressed.

2. Criteria for the identification of glacial deposits

The Earth has undoubtedly experienced past icehouse climates and glaciations which have left behind a characteristic signature. Investigation of the Pleistocene glacial episode, together with the intensive study of modern glacial environments, has provided a clearly defined set of geological criteria which are required in order to establish whether a suspected deposit is of glacial origin. The principal criteria used to determine whether particular deposits are of a glacial origin include abraded rock surfaces, polished pavements, chattermarks and roche moutonnée-like forms (see Table 1). Evidence of glacial marine (or lacustrine) deposition includes the presence of dropstones rafted by ice within a finer-grained host sediment although it is widely acknowledged that other mechanisms such as rafting by the roots of floating driftwood and algal mats, can also produce such features (see below).

Faunal and floral evidence may also be utilised to determine the presence or absence of cold or subfreezing polar conditions. More indirect evidence for glacial conditions may be derived from GCM simulations of climate. Additionally, palaeontological and sedimentological evidence has been used to infer globally synchronous sea level change related to large-scale changes in ice volumes. Periglacial features and the general range of cryoturbational structures produced by freeze–thaw processes (see Eyles and Paul, 1983) can also be used to infer at least seasonal sub-freezing conditions, although they are rarely recognised in Mesozoic successions (Sellwood and Price, 1993).

Glendonite carbonate nodules have been taken to reflect cold subaqueous depositional conditions (Kemper, 1987; Francis and Frakes, 1993). Glendonites are stellate aggregates which have pseudomorphed the mineral ikaite, a low-temperature poly-

Table 1
Principal criteria used to establish direct or indirect evidence for glacial or cool conditions

Geological / geomorphological feature	Reference
Direct evidence for ice	
Abraded rock surfaces illustrating striations, grooves, polished pavements, chattermarks	Harland et al. (1966), Hambrey and Harland (1981), Hambrey (1994)
Generally unsorted stone-rich beds, with wide range in grain size, irregular thickness and filling hollows and pre-existing palaeo-relief	Hambrey and Harland (1981), Hambrey (1994)
Drumlins, moraines and eskers	Hambrey and Harland (1981), Hambrey (1994)
Chattermark trails on garnets	Folk (1975), Gravenor (1979)
Angular quartz grains, with conchoidal fracture patterns	Krinsley and Doornkamp (1973)
Clay or calcareous coatings on larger stones	Yuelin et al. (1981)
Rock flour and loess	Hambrey (1994)
Direct evidence for sea / lake ice	
Dropstones rafted by ice, calved from ice masses terminating in water — characteristic features include anomalous size of clasts with a sediment which shows disruption of the laminae at the base and draping of sediment over the top of stones	Hambrey (1994), Bennett et al. (1996)
Bowl-shaped circular and elongate structures, subsequently filled by mud and sand formed by shore-ice	Dionne (1998)
Laminated sediments, varves	Hambrey (1994)
Indirect evidence for ice and ice sheets	
General Circulation Models of palaeoclimate	Ramstein et al. (1997), Price et al. (1998b)
Globally synchronous changes in sea level	Brandt (1986), Goldhammer et al. (1987), Kemper (1987)
Indicators of cool or cold conditions	
Periglacial and cryoturbational structures produced by freeze-and-thaw processes, ice wedge casts, sorted stone circles, polygonal patterned ground, pingos, solifluction lobes	Hambrey and Harland (1981), Eyles and Paul (1983), Hambrey (1994)
Glendonite nodules (ikaite) suggestive of cold subaqueous depositional conditions or cold deep marine settings	Shearman and Smith (1985), Kemper (1987)
Oxygen isotope palaeothermometry data from high latitudes (or extrapolated from lower latitudes)	Sellwood et al. (1994), Stoll and Schrag (1996), Ditchfield (1997)
Carbon isotope fluctuations	Weissert (1989), Weissert and Lini (1991)
Faunal and floral indicators (i.e., presence or absence of cold tolerant or intolerant species)	Frakes et al. (1992), Philippe and Thevenard (1996)
Morphologic (physiognomic) analysis of flora	Spicer and Parrish (1986)

morph of calcium carbonate which crystallises at temperatures close to 0°C but readily decomposes to calcite and water at higher temperatures (Shearman and Smith, 1985). Occurrences at temperate and tropical latitudes are known, but from deep (4 km) waters (Stein and Smith, 1986 cf. Markwick and Rowley, 1998). Oxygen isotope data derived from well preserved biogenic carbonate material and carbonate sediments interpreted in terms of temperature have also been widely used to infer cool or subfreezing marine conditions (Table 1). Problems encountered using this technique, particularly with respect to absolute temperature estimates, are related to the fact that the isotopic composition of seawater is known to have varied in the past in response to the formation and disappearance of ^{16}O-rich icecaps and local differences in evaporation, precipitation and freshwater runoff.

3. Preservation potential

Although certain sediments or landforms are readily recognised as being of a glacial origin, in order to be discovered within the geological record they must have a high preservation potential. The more indirect indicators of glacial conditions, although more equivocal, nevertheless have the distinct advantage of being easily preserved within the rock record. In contrast deposits such as till have a significantly lower chance of being preserved as they are formed in such a distinct erosive environment. According to Bjørlykke (1985), glacial sediments, in addition to features such as striations and characteristic reliefs, are likely to be removed by post-glacial erosion and therefore pre-Pleistocene glacially derived deposits are unlikely to be found close to the glaciation centres. For example, less than 6% of the total volume of glacio-clastic sediment produced by late Cainozoic ice sheets in North America remains on land (Bell and Laine, 1985). The bulk of the sediment flux is directed to the marine environment and deposited in deep water continental slope and submarine fan settings (Eyles, 1993). It is further suggested by Eyles (1993) that most sediments of glacial origin transferred to the marine environment are likely to be completely reworked, thereby eradicating any evidence of glacial origin. Such an observation may suggest that the dominant glacial facies types in the ancient record are likely to be marine debris flow diamictites and turbidites which may be impossible to recognise as of glacial origin. To suggest that all evidence of a glaciation is likely to removed or reworked is, however, unjustifiable as glaciations are now well documented for a number of periods in the geological past, as noted above (Fig. 1), including late Precambrian and Palaeozoic times (e.g., Hambrey and Harland, 1981; Crowell, 1982; Boardman and Heckel, 1989; Frakes et al., 1992). Continental rift basins provide the most favourable environments for preservation of glacial sediments (Bjørlykke, 1985). Markwick and Rowley (1998) note that high-latitude rift basins of Mesozoic and early Cainozoic age are preserved, such as in Spitsbergen in the Triassic and Jurassic and in southeastern Australia in the mid–late Cretaceous. Whether these areas contain recognisable glacially-derived sediments and landforms is discussed below.

The interplay between eustasy, subsidence and therefore accommodation space also potentially complicates preservational biases. In particular, sediments deposited in transgressional episodes are more likely to preserved, whilst glacial sediments be reduced in thickness if related to glacio-eustatic hiatuses and therefore relatively under-represented.

4. The Mesozoic evidence

Earlier studies by Epshteyn (1978), Hambrey and Harland (1981), Kemper (1987), Frakes and Francis (1988) and Frakes et al. (1992) have proven excellent compilations of glacial data from certain times during the Phanerozoic and have provided invaluable sources of data. To create a visual record of the distribution of possible glacially derived sediments, the evidence described below has been compiled on palaeogeographic reconstructions of the late Triassic, late Jurassic and late Cretaceous (Fig. 2a–c).

4.1. North America, Europe, and Siberia

Occasional exotic clasts within the English Chalk (e.g., Double, 1931; Hawkes, 1951) and underlying greensands (Hawkes, 1943) have been considered as possible glacial dropstones by Jeans et al. (1991) who invoke a depositional mechanism involving transport by floating coastal ice to support a theory of a glacial control upon the development of the Cenomanian–Turonian $\delta^{13}C$ anomaly. However, the exact origin of these clasts is certainly equivocal (Sellwood and Price, 1993; Chumakov, 1995) as roots of floating trees have been proposed as a mechanism equally capable of transporting such materials (Hawkes, 1951; Bennett and Doyle, 1996; Bennett et al., 1996; Markwick and Rowley, 1998). The exotic clasts within the English Chalk range in size from pebbles to boulders, and although they exhibit occasional striations on clast surfaces, display few other features which may allude to a glacial origin such as disruption of the laminae at the bases of clasts (see Table 1). A recent and detailed study of these exotic stones (now present in museum collections) has been undertaken by Chumakov (1998), who analysed particularly clast surfaces by scanning electron microscopy. As none of the stones examined exhibited signs of glacial or seasonal-ice abrasion, Chumakov (1998), instead interpreted striations as representing traces of Cretaceous animals, which scraped food off pebble surfaces. Similar erratic clasts (composed of largely of gneisses, quartzites and granites) have also been described from the Maastrichtian of Denmark (Noe-Nygaard, 1975) and the Turonian of Münsterland, western Germany by

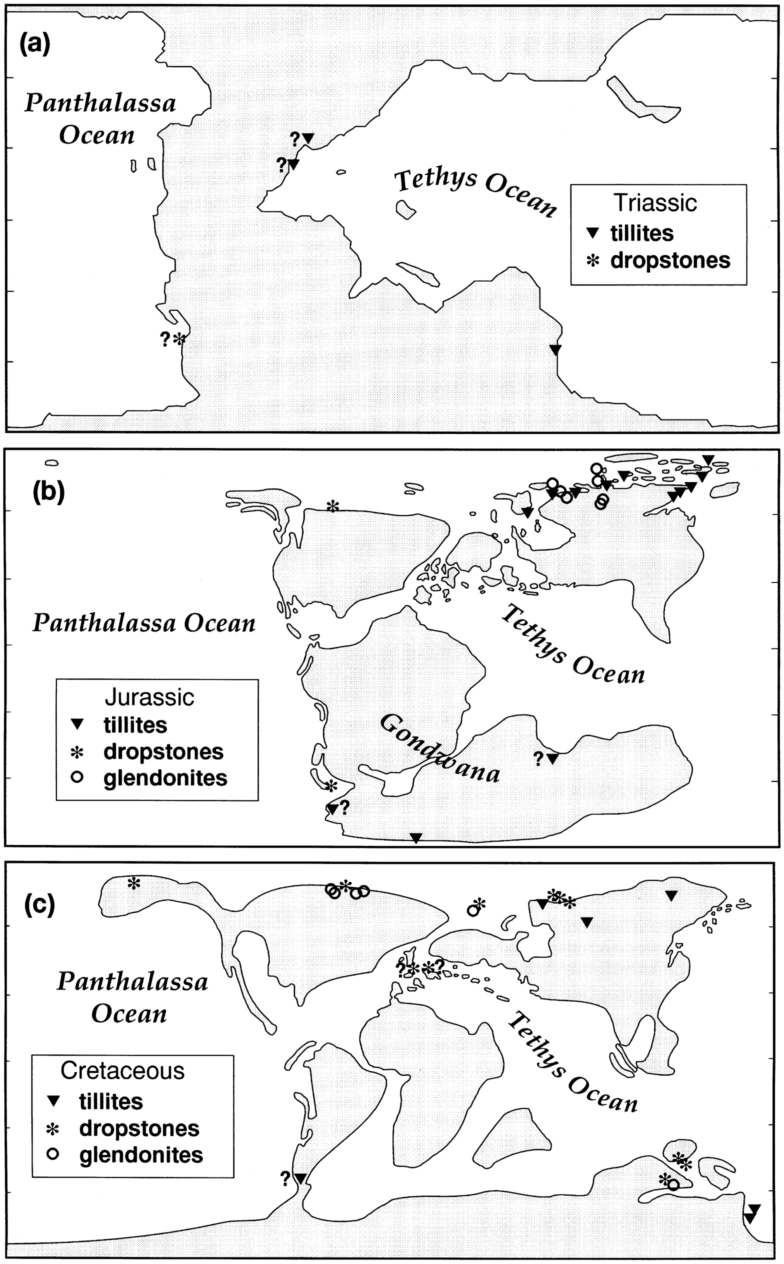

Fig. 2. Distribution of possible glacially derived sediments and glendonites plotted on (a) late Triassic (Carnian, from Wilson et al., 1994), (b) late Jurassic (Kimmeridgian, from A.G. Smith, pers. commun.) and (c) late Cretaceous (Cenomanian, from A.G. Smith, pers. commun.) palaeogeographic reconstructions. Data derived from references cited within the text. Note the category tillites includes all deposits described as tills, unsorted pebbly claystones and conglomerates.

Schmidt and Schreyer (1973) who also favour deposition by driftwood or floating seaweeds rather than ice.

Within the Sverdrup Basin in Arctic Canada outsize clasts also occur within Upper Jurassic–Lower Cretaceous shales and have been attributed to ice rafting (Embry, 1984; Frakes and Francis, 1988). Kemper (1983; 1987) describes widespread glendonites, indicative of cold glacial subaqueous depositional conditions, of early Cretaceous (Valanginian and Aptian) age also from the Sverdrup Basin, which may provide support for the advocated ice rafting origin for dropstones. The early Cretaceous (Hauterivian–Barremian) Pebble Shale Member of the Kongatuk Formation in northeastern Alaska has also been considered to be of glacio-marine origin (e.g., Frakes and Francis, 1988). The Pebble Shale Member contains flattened highly polished chert pebbles and may have been deposited in a deep water environment (Detterman et al., 1975).

Erratic clasts within the Cretaceous (Valanginian–Hauterivian and Aptian–Albian) Innkjegla member from Spitsbergen have been interpreted as material transported by shore or winter ice (Kellogg, 1975; Dalland, 1977; see also Pickton, 1981). Birkenmajer and Narebski (1963) consider these erratic clasts as material transported by driftwood or kelp, although an ice-transport origin may be supported by the occurrence of glendonites from the Valanginian and Aptian of Spitsbergen described by Kemper (1983).

A number of deposits with affinities to glacial tillites of Mesozoic age have also been described from eastern Europe and Russia. Chumakov (1981a) describes possible tillites from the middle Volga region of the former USSR. These breccias are possibly Triassic in age and are composed of sand and clay matrix containing numerous gneiss fragments deposited in a broad cone-shaped depression. Although these deposits have been considered to have resulted from the action of Triassic glaciers, the shape of the body of the breccias together with their composition, would suggest an infilling of a basin of a meteorite impact origin most probable (Chumakov, 1981a).

Epshteyn (1978) and Chumakov (1981b) describe extensive Siberian Jurassic and Cretaceous tillites stretching from the Yenisey River eastwards to the Oloy ridge (Fig. 2b and c). The principal characteristic of these deposits according to Epshteyn (1978) are non-bedded, silty and pebbly claystones. The pebbly claystones often form separate beds ranging from < 1 to 7 m in thickness and have been considered to be glacio-marine in origin or formed by seasonal ice of mountain rivers (Epshteyn, 1978; Golbert, 1979). A recent study by Chumakov and Frakes (1997) re-investigating some of these Jurassic (Bathonian–Oxfordian) deposits north of Magadan city between the upper courses of the Kolyma and Indigirka rivers, northeast Asia, however, found no convincing evidence of ice rafted sediments in the late Jurassic sections. Sediments previously attributed to ice rafting display characteristics of mass movement, including contorted bedding and evidence of turbidity currents. The Callovian–Oxfordian sediments of the Artyk River section described by Chumakov and Frakes (1997) do contain, however, rare star shaped carbonate concretions resembling glendonites. The clasts most likely to be of ice-rafted origin occurred within the Bathonian Svetlyi Formation (Chumakov and Frakes, 1997). Nevertheless, many of the ice-rafted deposits described by Epshteyn (1978) and Chumakov (1981b) are from high palaeolatitudes and compare favourably with the abundant glendonite occurrences of mid-Jurassic and early Cretaceous age described by Kaplan (1978) from the Taymyr peninsular eastwards to the Lena River (Fig. 2b and c). Kaplan (1978) also describes glendonites of Pliensbachian age in the Lena River area, but notably biostratigraphical age control for these occurrences and those of the mid-Jurassic and early Cretaceous is poor.

Possible evidence of glacial conditions during the Carnian (late Triassic) has been proposed by Seffinga (1988) who describes feldspar-rich sandstones and shales with illite, chlorite and mixed-layer clay minerals thought to have been deposited in a deltaic environment. Evidence for prevalent glacial conditions appears unsubstantiated. Furthermore, such deposits appear at an unlikely palaeolatitude (see Fig. 2a). Seffinga (1988) also suggests that non-marine late Triassic breccia-like conglomerates, containing large angular rock fragments from Japan may be of glacial origin. These sediments have, however, been attributed to deposition influenced by tectonic activity (Tokuyama, 1961).

4.2. Antarctica

A poorly sorted clastic rock, of middle Jurassic age, in South Victoria Land, East Antarctica, has been identified as the product of glacial deposition by Gunn and Warren (1962) and named the Mawson Tillite. The diamictite sediments consist of distorted granulated rocks, overlain by similarly granulated rocks derived from a basaltic volcanic material. The Mawson Tillite has since been re-interpreted by Borns and Hall (1969) and Ballance and Watters (1971) as a unit of volcanic origin and consisting largely of primary and reworked volcanic material (see also Hallam, 1975; Hambrey, 1981). More recently, however, Woolfe and Francis (1991) record a previously undescribed lower diamictite present within the Mawson Formation, which has no volcaniclastic component. Their interpretation is based upon an extensive erosion surface, the presence of possible ice contact drag-folding and notably striated clasts (see Table 1). The age of the glaciation is proposed as early–middle Jurassic based upon the occurrence of a late Triassic microflora in the underlying formation and a Middle Jurassic radiometric age for the overlying formation (Woolfe and Francis, 1991).

Other deposits suspected of being of glacial origin and possibly of Jurassic age have also been located in Antarctica. In the Mount Blackburn area, Doumani and Minshew (1965) describe a 15-m tillite composed of well-faceted, striated and grooved boulders embedded within a light green matrix which is inferred to be Jurassic or possibly younger. Similarly, Craddock et al. (1964) have postulated that a glacial erosive surface on a basement complex may be Cretaceous or younger from the Jones Mountain area of west Antarctica.

4.3. South America

Numerous alleged tills and breccias have also been recorded from southern South America. Triassic slates with pebbles and boulders which have an alleged glacial component have been described by Cecioni (1981a) from the El Toco Group, Atacama Desert, Chile. However, the pebbles and boulders, thought to be glacial in origin, may have been reworked by rivers during late Palaeozoic–Triassic times and deposited as turbulent shelf facies composed of shelf flysch deposits (Cecioni, 1981a). In a detailed review of the El Toco Group sediments Charrier (1986) also rejects a glacial origin for these deposits based in part upon the presence of laminated sediments indicative of subaqueous deposition. Further, as more accurate data regarding the age of the El Toco Group sediments and relationships with several other units known in the area are lacking, it is difficult to assign to them a precise origin (Charrier, 1986).

Cecioni (1981b) describes breccias, and claystones with granitic pebbles within the late Jurassic Flamenco Formation and proposes that these deposits where formed possibly by mountain glaciers. A suspected glacial deposit consisting of conglomerates with intercalated shales from the Cretaceous Lago Sofia Formation of Chilean Patagonia has also been described by Cecioni (1957). This deposit and associated striations, originally thought to have been formed by direct glacial erosion, has since been reinterpreted as being formed by catastrophic introduction of conglomerate into a flysch environment (Scott, 1966; Hallam, 1975; Cecioni, 1981c).

4.4. Australia and New Zealand

Within Australia, there are a number of deposits of Mesozoic age which have been attributed to a glacial or ice-rafting origin. Frakes and Krassay (1992) describe rounded clasts up to small boulder size within fine-grained strata of late Jurassic–Cretaceous (possibly late Albian) age from the Carpentaria Basin located in the eastern part of Northern Territory and northwestern Queensland. Frakes and Krassay (1992) consider the clasts typical of being transported by ice rafting, rather than mechanisms such as floating tree roots and hence infer sub-freezing temperatures sufficient to allow the formation of ice floes along rivers and marine shorelines during the late Mesozoic. These late Jurassic–early Cretaceous sediments generally continue southward and are equivalent to the Bulldog Shale in southern Australia (Alley and Rogers, 1985). Woolnough and David (1926), Frakes and Francis (1988), Sheard (1990) and Francis and Frakes (1993) also describe boulder size clasts, considered to be glacial dropstones from the Bulldog Shale. These studies have moreover recorded the occurrence of glendonite nodules also indicative of cold subaqueous temperatures. Examination of the larger clasts by Frakes and Krassay (1992) did not reveal striae or chattermarks, although these features have been described by David (1950) from the Bulldog Shale (but striation may have occurred before the Cretaceous). In a detailed description of Valanginian to Albian dropstones within the Bulldog Shale and Cadna-owie Formation of the Eromanga basin, Frakes et al. (1995) also attributed the transport mechanism to seasonal ice formed in winter along stream courses and strandlines. Markwick and Rowley (1998), in an analysis of the Lower Cretaceous erratics of Australia, attribute their origin to reworking from earlier diamictite deposits and invoke an emplacement mechanism such as tree-rafting. Rafting by driftwood or floating algae was, however, considered unlikely by Frakes et al. (1995) as fossil woods were found mainly in nearshore areas of the basins and large algal mats were not observed. Moreover, a recent study by De Lurio and Frakes (1999) which involved the analysis of the oxygen isotopic composition of glendonites from the dropstone facies estimated late Aptian temperatures to be in the range of 0–5°C.

Further evidence of cool or sub-freezing temperatures in Australia has been derived from the Gippsland Basin where rare cryoturbational structures have been identified by Constantine et al. (1998) in fluvial-lacustrine sediments of the (Aptian–Albian) Wonthaggi Formation. These structures are associated with seasonal freezing and thawing of soils, where mean annual air temperatures ranged from −6° to 3°C, a range in agreement with the isotopic data of Rich et al. (1988) and Gregory et al. (1989) (see below).

New Zealand has been located at high palaeolatitudes (60–85°S) throughout the Mesozoic (Smith et al., 1994) and therefore conceivably should contain plentiful deposits of glacial origin if high latitude ice during this time is a reality. An early Triassic (late Scythian or early Anisian) deposit from Eglington Valley, South Island, consists of scattered and rounded blocks including chert, granite, and basalt, within a black silty matrix and resembles a diamictite (Waterhouse and Flood, 1981). Other deposits in New Zealand which may be of glacial origin include the early Cretaceous (?Albian) Hawks Crag breccia, the comparable Jay Breccia and the ?Aptian–Turonian Kyeburn Formation Breccia located in the Nelson region in northern part of South Island. The Hawks Crag breccia reaches over 1500 m, and consists of a poorly sorted angular breccia with granitic cobbles and boulders up to 3 m across with interbedded silt and sand layers (Beck and Natham, 1978). These breccias are clearly rapidly accumulated sediments derived locally from areas of high relief and may be of glacial, fluvioglacial or alluvial fan origin, although none of these depositional mechanisms adequately account for all the observed features (Beck and Natham, 1978). More recently, Tulloch and Palmer (1990) have suggested a tectonic control influencing the provenance of the granitic cobbles. Similar deposits, also of Cretaceous (Aptian and Albian) age have been described by Waterhouse and Flood (1981) who describe poorly sorted breccias within a sandy matrix and well rounded pebbles with polished surfaces from southeast corner of North Island. These deposits resemble glacial dropstones, but some degree of recycling is alluded to by Waterhouse and Flood (1981) from underlying conglomerates. Waterhouse and Flood (1981) also describe pebbly siltstones resembling a diamictite of late Cretaceous (Campanian) age. These diamictites are poorly sorted with a matrix of angular quartz and rock flour, although no pebbles appear to be striated.

5. Indirect evidence of Mesozoic glacial conditions

5.1. Isotopic indicators of temperature

As noted above, in addition to direct evidence of glacial conditions, more indirect evidence is contained within the sedimentary record. Such evidence may signal cool or sub-freezing temperatures or a requirement for glacial conditions to explain sedimentary features or palaeontological patterns and therefore naturally demands a degree of conjecture with respect to the presence of polar ice.

One of the most common methods of establishing quantitative values for past temperatures has been the use of oxygen isotopes derived from well-preserved biogenic carbonate material. A number of studies focusing particularly on high palaeolatitudes in northern (Ditchfield, 1997; Riboulleau et al., 1998) and southern hemispheres (Lowenstam and Epstein, 1954; Dorman and Gill, 1959; Pirrie and Marshall, 1990; Ditchfield et al., 1994; Pirrie et al., 1995) have produced temperature data, which if extrapolated polewards, are not incompatible with high-latitude sub-freezing conditions during the late Jurassic

(Tithonian) and early Cretaceous (Valanginian, Aptian and Albian). For example, Pirrie et al. (1995) calculate palaeotemperatures averaging about 10°C at a palaeolatitude of 55°S, based upon isotopic analysis of Albian belemnites from the Gearle Siltstone of Western Australia. The isotopically derived palaeotemperatures of Ditchfield et al. (1994) have recently been compared with geochemical estimates of weathering and sediment maturity by Dingle and Lavelle (1998). These authors describe coincident periods of low chemical weathering and low palaeotemperatures, but conclude these are not consistent with frigid glacial conditions.

Other studies (e.g., Sellwood et al., 1994; Price et al., 1998a) investigated, in particular, mid-Cretaceous palaeotemperatures of middle and lower palaeolatitudes and also extrapolated the results polewards. The study of Sellwood et al. (1994), who combined oxygen isotopic data of well-preserved planktonic foraminifera with isotopic data derived from belemnites, suggested also the possibility of sub-freezing polar temperatures (but see also Crowley and Kim, 1995; Huber et al., 1995) although they considered the pole-to-equator temperature profile as a coldest case scenario (Price et al., 1996). Other studies also assessing temperature variation of high southern latitudes during the late Jurassic and Cretaceous using isotopic ratios from belemnites and foraminifera (e.g., Bowen, 1966; Stevens and Clayton, 1971; Barrera et al., 1987; Huber et al., 1995; Price and Sellwood, 1997; Fassell and Bralower, 1999) certainly support the notion that high latitudes were periodically warmer and ice-free.

All such isotopic studies utilise variations of the temperature equation originally proposed by Urey et al. (1951), which uses an estimate of the isotopic composition of seawater. In calculating the palaeotemperatures many such studies (e.g., Ditchfield et al., 1994; Ditchfield, 1997; Price and Sellwood, 1997) have used a $\delta^{18}O_{seawater}$ value of -1.2‰ PDB (equivalent to -1.0‰ SMOW), suggested appropriate by Shackleton and Kennett (1975), for an ice-free Earth. An obvious problem of a circular nature in using such a value becomes immediately apparent. Although such isotopic palaeotemperature studies may suggest sub-freezing temperatures using a $\delta^{18}O_{seawater}$ value of -1.2‰ (PDB); if, however, polar ice is a reality, such a value may become somewhat inappropriate. Hence, Rowley and Markwick (1992) highlight the potential problems of using oxygen isotope record to infer the presence or absence of polar ice. In a recent study, however, Price et al. (1998a), using an estimation of the magnitude of a simulated Cretaceous ice sheet, estimated an isotopic composition of ~ -0.9‰ (PDB) for mean ocean water during the Cretaceous when a small icecap was present. Using such a value in the temperature equation of Urey et al. (1951) changes only slightly the isotopically derived palaeotemperatures and hence the results are not significantly altered.

Evidence for Cretaceous icehouse interludes have also been based upon carbon isotope fluctuations (e.g., Weissert, 1989; Weissert and Lini, 1991). Weissert (1989) and Lini et al. (1992) have asserted that greenhouse climates with high levels of atmospheric CO_2 lead to increases in precipitation, weathering rates and hence terrestrial runoff. This leads to a concomitant rise in nutrient input into the oceans and accelerated carbon cycling, giving rise to positive carbon isotope excursions. Negative carbon excursions during the early Valanginian, the mid-Hauterivian–Barremian and around the Aptian–early Albian boundary, are thus times of decelerated carbon cycling and are correlated with cool or icehouse climates by Weissert and Lini (1991). According to Chumakov (1995), the Cretaceous icehouse interludes based upon such $\delta^{13}C$ fluctuations are unconvincing and, even if the excursions were related to cooling events, there is no reason to consider them strong enough to have resulted in glaciation. Partial support of the theory proposed by Weissert and Lini (1991) and Lini et al. (1992) is derived from a tentative correlation of positive carbon excursions with sea level highstands and indicators of humidity, whilst negative excursions correlate with evidence of aridity derived from clay mineral analysis (e.g., Weissert and Lini, 1991; Frakes et al., 1992; Price et al., 1998a).

A somewhat different interpretation of isotopic values has been presented by Matthews and Poore (1981) and Prentice and Mathews (1991). They propose, for the Tertiary, modification of the isotopic composition of seawater on the basis of polar ice volumes leads to unrealistically cool tropical sea surface temperatures. Further, they suggest that there is no compelling evidence on which to base ice-volume estimates and that tropical sea surface temperatures may have stayed constant through the Cainozoic, and back into the Cretaceous at a theoretical 28°C. By assuming a constant tropical sea surface temperature, they suggest the probable occurrence of significant volumes of ice in polar regions at least since the Eocene and perhaps even throughout much of Cretaceous time. If the assertion by Matthews and Poore (1981) that tropical sea surface $\delta^{18}O$ variation is constrained as a function of ice volume and that $\delta^{18}O$ values more positive than −3‰ for tropical marine skeleta are evidence for the existence of ice, this would indicate significant amounts of ice throughout much of the Cretaceous. Only Cenomanian times would escape ice cover. Such a concept may not always be in conflict with geological evidence, but to assume a constant of 28°C appears intuitively unlikely although such tropical temperatures have recently been suggested from GCM simulations for the mid-Cretaceous (e.g., Barron et al., 1995). In contrast, Miller et al. (1987) suggest that ice-free conditions existed prior to the Pliocene, based upon bottom water palaeotemperature estimates derived from $\delta^{18}O$ compositions of benthic foraminifera. As pointed out by Markwick and Rowley (1998) this approach is also problematic, since bottom water temperatures do not necessarily reflect ambient temperatures in polar regions, particularly if deep circulation was in the past driven by warm saline bottom water.

5.2. Faunal and floral evidence

A great deal of information regarding the temperature of Earth during the Mesozoic has been gained from flora and fauna and in particular the analysis of the patterns and degree of provinciality. It has been widely considered that in particular the early Jurassic period was characterised by low faunal provinciality (e.g., Hallam, 1975; Frakes, 1979), possibly due to equable climates and the lack of polar ice caps. Faunal provinciality became marked from Middle Jurassic times onwards (Frakes, 1979; Doyle, 1987; Enay and Cariou, 1997) and two major faunal provinces existed in the northern hemisphere, the northern Boreal realm and the lower latitude Tethyan realm. A southern hemisphere Austral realm corresponding to the northern Boreal realm has also been recognised (e.g., Stevens, 1973; Crame, 1993). Crame (1986; 1993) has identified marked bipolarity in the distribution of certain bivalves during the Jurassic (Pliensbachian and Tithonian) and early Cretaceous (Aptian–Albian). Provinciality amongst cephalopod faunas became most pronounced at the end of the Jurassic, a pattern continued through to the Barremian with minor modifications reflecting transgressive and regressive pulses (Casey and Rawson, 1973). Such a pattern of provinciality essentially broke down in the early Aptian, related to a series of transgressive events (Casey and Rawson, 1973; Mutterlose, 1992, 1998), resulting in extensive faunal overlap and a tendency towards a global homogenisation of many marine biota (Hallam, 1994). Because such patterns of provinciality among Mesozoic brachiopods and certain molluscan faunas roughly follow lines of latitude, and diversity is generally lower in the higher-latitude province, climate and in particular temperature has been considered to be an important controlling factor (e.g., Rawson, 1973; Stevens, 1973; Middlemiss, 1984). The possible existence of Boreal and Austral realms, delineated by temperature, during parts of the Mesozoic certainly does not preclude, but instead lends support to the existence of cold or even sub-freezing conditions at the poles. This interpretation has, however, been questioned by Hallam (1975; 1984), Doyle (1987), Crame (1993), Enay and Cariou (1997) and Cecca (1999) who stress that other factors such as the distribution of continents and oceans, salinity and seasonality were likely to be more important than temperature alone in controlling faunal provinciality. Although these latter authors recognise a latitudinally delineated Jurassic ammonite distribution pattern, with a lower diversity Austral fauna, they suggest that high latitude seasonal effects are likely to have resulted in environmental instability controlling the structure of ecosystems and different tropic levels. Furthermore a study conducted by Hallam (1972) on Pliensbachian and Toarcian bivalves revealed a tendency for diversity to increase, rather than decrease, from the Tethyan to Boreal realm. In a recent study of the distribution of Jurassic bivalves, Liu et al. (1998) conclude that temperature must have contributed to faunal provincialism, but stress that other environmental and palaeogeographic factors were also important and likely to have varied considerably throughout the Jurassic.

Wing and Greenwood (1993), also note that the climatic preference of the nearest living relative may not accurately reflect those of extinct forms because of evolutionary change, extinction or geographic range restriction related to non-climatic factors. This may also be illustrated by the occurrence of dinosaurs and large amphibians at high latitudes (e.g., Colbert, 1962; Olivero et al., 1991; Hammer and Hickerson, 1994). Hammer and Hickerson (1994), for example, use the occurrence of a theropod dinosaur of Jurassic age from Antarctica as evidence for a warm and equable climate. However, it may have been that dinosaurs were warm blooded and able to tolerate colder winters (Bakker, 1978, 1980; see also Constantine et al., 1998) or alternatively dinosaurs may have seasonally migrated from cool polar areas to warmer climates (e.g., Axelrod, 1984; Parrish et al., 1987). A late Cretaceous (Turonian–Coniacian) vertebrate assemblage, including crocodile-like reptiles from the Arctic, has recently been described by Tarduno et al. (1998), the presence of which have been used to suggest mean annual temperatures greater than 14°C (based upon the thermal limits of modern crocodiles).

Important work on Jurassic phytogeography in relation to climate has been undertaken by Ziegler et al. (1993) who analysed Middle and Upper Jurassic Eurasian floras. These authors assigned Siberian floras to a cool temperate biome, characterised by cold winters and warm summers, implying polar conditions considerably warmer than today. The morphology (physiognomic) based approach has likewise been used with great success in reconstructing Mesozoic temperatures, particularly in palaeobotanical studies (e.g., Wolfe, 1979; Spicer and Parrish, 1990; Spicer et al., 1993). Morphological methods assume that characteristics of species or communities bore the same relation to climate in the past that they do now. Leaf margin analysis has yielded a Cenomanian mean annual temperature of 10 ± 3°C and 5°C during the Maastrichtian on the coastal plain of northern Alaska (Spicer and Parrish, 1986, 1990). More recently Parrish et al. (1998), using similar leaf margin analysis and vegetational physiognomy, indicate that a mid-Cretaceous flora from the middle Clarence Valley of New Zealand grew at a mean annual temperature of 10°C, a value identical to that derived from coeval floras from northern Alaska. Such quantitative palaeotemperature estimates have been used by Spicer and Parrish (1990) to infer that permanent ice was likely in Alaska above 1200 m during the Cenomanian and 1000 m during the Maastrichtian. Recent evidence using physiognomic methods by Herman and Spicer (1997) provides indications for high latitude warmth during the late Cretaceous (Turonian and Coniacian) and that the Arctic ocean remained above freezing even during the winter during these times.

Vascular plants also display a variety of features that can be correlated with climate. In a study of the Mesozoic wood genus *Xenoxylon*, Philippe and Thevenard (1996) suggested that its distribution compared favourably with relatively cool and wet climates and appears to have preferred mean annual temperatures between 5–15°C. During intervals within the Jurassic *Xenoxylon* occurred at lower latitudes and was absent at higher latitudes, notably in the late Pliensbachian–early Toarcian and Bajocian–middle Bathonian. Such an observation may suggest that these higher latitudes were even colder than the favoured mean annual temperature range. Hallam (1998a) suggests, however, that possibly the key factor controlling such a distribution pattern may be more related to palaeogeography, rather than climate and notes that further evidence is required in terms of the botanical affinities and ecology of *Xenoxylon*. Analysis of high-latitude Mesozoic Australian and Antarctic floras has been undertaken by numerous authors (e.g., Douglas and Williams, 1982; Francis, 1986; Detterman, 1989; Read and Francis, 1992; Retallack and Alonso-Zarza, 1998). These latter authors suggest that the combination of roots, logs, leaves of woody plants and the degree of chemical weathering and clay formation within paleosols, are indicative of temperate climatic conditions in Antarctica during the middle Triassic. Silt infiltration structures within the paleosols are considered to be indicative of a seasonally snowy climate, but no evidence of ice wedges or other permafrost features was observed (Retallack and Alonso-Zarza, 1998). During mid-Cretaceous (Albian–Cenomanian) times temperate gymnosperm rainforests first appeared in Antarctica, to be replaced by cool-temperate high rainfall forests during the latter stages of the Cretaceous. The characteristics of these floras have been taken to suggest frost-free conditions (Francis, 1986). Douglas and Williams (1982) interpret the Aptian–Albian floral information from Victoria, Australia as indicating cool and wet temperate climates an interpretation compatible with the isotopically derived palaeotemperatures noted above (see also Frakes et al., 1995). It is of note that Read and Francis (1992) propose that some tree species growing at high latitudes during the Cretaceous and Tertiary would have been tolerant to prolonged periods of darkness, although if the winters were both warm and dark many species were unlikely to have survived. A combination of cool winters and moist, warm summers is likely to be the most favourable regime for plant survival (Read and Francis, 1992).

5.3. Sea level fluctuations

Many studies have recorded large and globally synchronous changes in Mesozoic sea level (e.g., Brandt, 1986; Goldhammer et al., 1987; Haq et al., 1987, 1988; Plint, 1991; Hallam, 1992; Sahagian et al., 1996). Such investigations have sometimes invoked the presence of fluctuating polar ice volumes as a primary mechanism to account for such changes and Bjørlykke (1985) and Kemper (1987) note that eustatic sea level changes are an important criterion for recognising glacial periods.

The sea level curve of Haq et al. (1987) (Fig. 4) implies sea levels rose and fell over 100 m a number of times during the Mesozoic (but see also the criticisms of Hallam (1992)). Haq et al. (1987) distinguish two orders of eustatic curves, a ‘long term’ and a ‘shorter term’ curve relative to present-day sea level. Haq et al. (1987) suggest that the longer term curve maps the overall trend in sea level which may be accounted for by variation in the volume of the ocean basins. Vail and Haq (1988) maintain that only glacial eustasy operates with sufficient magnitude and frequency to control the short-term curve.

Goldhammer et al. (1987) and Masetti et al. (1991) invoke the possible existence of sizeable ice cover during the middle and late Triassic, based upon evidence for high-frequency Milankovitch influenced sea level oscillations recorded in platform carbonates of the Dolomite region of northern Italy. It is considered by both Goldhammer et al. (1987) and Masetti et al. (1991) that tectonic movements cannot operate on a sufficiently rapid timescale to account for the observed high-frequency sea level changes and hence possibly leaving only glacio-eustatic mechanisms to control sea level change. In strata of late Cretaceous age from France and Canada, Plint (1991) and Malartre et al. (1998) also recognise sea level oscillations, frequently manifest as regional erosional surfaces and by default also infer a glacio-eustatic control. If such changes in sea level are glacio-eustatically controlled, this would imply that a significant number of glaciations of sufficient size, to affect global sea level, occurred during the Mesozoic (see Fig. 4).

However, if ice caps are either absent or negligible during the Mesozoic, alternative mechanisms to account for the observed changes in sea level are required. One interpretation could be that apparent sea level changes are caused by regional tectonic events. As noted above, however, tectonic movements have been considered to operate at neither a sufficiently rapid timescale and obviously not on a global scale. An alternative mechanism, was proposed by Cloetingh et al. (1985) and Cloetingh (1986), who suggested that variations of within-plate lithospheric stress could account for rapid relative sea level changes. Likewise, Cathles and Hallam (1991) put forward a similar model involving stress-induced changes in plate density and suggested these could account for many of the transgressions and regressions traceable over areas larger than individual sedimentary basins. Such epirogenic movements may account for the sea level changes across the Triassic–Jurassic boundary where rates of change are comparable with rates induced by glacio-eustatic mechanisms (Hallam, 1997).

Other possibilities to account for global changes in sea level, include the thermal expansion and contraction of the oceans and desiccation of isolated ocean basins. For example, desiccation of the present Mediterranean would cause a rise of global sea level in the order of 12 m (Donovan and Jones, 1979). Although a rapid rise of sea level would be likely (~ 1 cm/year), Donovan and Jones (1979) anticipate that only a 15-m sea level change is to be expected from the operation of this mechanism in the past. Hsü and Winterer (1980) suggest, however, that evaporation of a large basin in the South Atlantic during the early Cretaceous could have provoked a 60-m sea level rise elsewhere. This latter figure comes significantly closer to the purported sea level variation indicated by the Haq et al. (1987) curve.

Jacobs and Sahagian (1993) alternatively propose that in times of postulated limited ice volume, Milankovitch-driven monsoonal fluctuations could influence lake and ground water storage and have the potential to produce small fluctuations in sea level, particularly in the Triassic. Hay and Leslie (1990), also suggest that Milankovitch-driven changes in the volume of groundwater may be capable of producing about 10–20 m of eustatic change over periods of only 10^4 to 10^5 years. Such a mechanism, seems insufficient to account for globally synchronous changes in sea level of large magnitude. Lehmann et al. (1998) do, however, suggest that changes in the storage capacity of aquifers and lakes, in conjunction with the thermal expansion and contraction of ocean water, could account for metre-scale cycles observed in early Cretaceous carbonates and evaporites from northeastern Mexico.

The sea level curves of Haq et al. (1987) have received criticism from a number of different viewpoints (e.g., Christie-Blick et al., 1988; Hallam, 1992, 1998b; Miall, 1992, 1993, 1994; Rowley and Markwick, 1992). Christie-Blick et al. (1988) suggest that the eustatic sea level changes invoked by Haq et al. (1987) are purely conjectural and represent severe overestimates, thus negating the need for such a controversial mechanism of waxing and waning polar ice sheets. Miall (1992; 1993) proposed that although the magnitude of sea level changes implied by Haq et al. (1987) may be more or less correct, they were not, however, synchronous, thus also negating the need for a glacio-eustatic mechanism. Further, Miall (1994) argues that current dating techniques do not permit the level of biostratigraphic accuracy and precision in sequence correlation required and Hallam (1992) highlights the underestimation of the role of regional tectonics when constructing the sea level curve.

In a detailed study, Rowley and Markwick (1992) used the Haq et al. (1987) sea level curve to retrodict the areal coverage of ice for the past 145 Ma and to retrodict the $\delta^{18}O$ of sea water (to indicate sequestered water volumes). The implied ice coverage on average was 40% of the Antarctic ice-sheet, which would suggest that the Earth was significantly affected, if not dominated by ice since the late Jurassic (Rowley and Markwick, 1992). However, variations in observed $\delta^{18}O$ values from the early Cainozoic values did not correlate with the Haq et al. (1987) retrodicted values and in fact many ‘anti-correlated’. Hence, Rowley and Markwick (1992) concluded that the magnitudes and very existence of many of the short term eustatic oscillations of Haq et al. (1987) during the late Jurassic–Cretaceous are unsubstantiated. In a recent analysis of early Cretaceous (Barremian–Valanginian) sediments Stoll and Schrag (1996), however, propose that the Sr concentration of seawater could be sensitive to rapid sea level changes. When sea level drops, Sr-rich aragonite on the continental shelves is exposed and altered to calcite and up to 90% of the Sr in the aragonite can be suddenly released to the oceans (Harris and Mathews, 1968; Stoll and Schrag, 1996). A correlation is recorded by Stoll and Schrag (1996) between episodes of low sea level which are reflected by high concentrations of Sr and positive oxygen isotope values indicative of low temperatures, high ice volume or both.

5.4. Evidence for glacial meltwaters

Oxygen isotope data from carbonate cements in early Cretaceous concretions from Victoria, Australia have been used to infer the isotopic compositions of meteoric fluids present at the time of concretion growth (e.g., Rich et al., 1988; Gregory et al., 1989). These authors propose that meteoric fluids with $\delta^{18}O$ values as low as $-20‰$ were involved in the precipitation of the early calcites and are comparable with $\delta^{18}O$ of calcites formed beneath modern glaciers. Gregory et al. (1989) suggest their data indicate mean annual temperatures of less than 5°C and perhaps as low as -6°C (see also Constantine et al., 1998 and above) and taken to be indicative of the presence of seasonal ice and possibly permanent ice at high elevations or in the interior of the Antarctic continent itself. Palaeotemperature estimates based upon oxygen isotope ratios of calcite derived from concretions have yet to be fully accepted (e.g., Spicer and Corfield, 1992; Spicer et al., 1993). The more recent studies of Ferguson et al. (1993; 1999) have nevertheless have reconfirmed temperatures of $0 \pm 5°C$ during the Aptian–Albian based upon isotopic analysis of materials from the southern coastal basins of Australia. Moreover, as noted above the study by De Lurio and Frakes (1999) which involved the analysis of the oxygen isotopic composition of glendonites from dropstone facies of Australia also estimated a similar temperature range.

Recent research by Blattner et al. (1997) has also invoked the presence of ice during the Cretaceous to account for highly depleted ^{18}O values derived from metamorphic and igneous terranes. Such depleted $\delta^{18}O$ values are thought to be indicative of highly depleted meteoric waters which could only be sourced from glacial melts. Additionally, because water–rock interaction is often incomplete even where it has occurred, Blattner et al. (1997) suggest that the lack of depleted values is poor evidence for the lack of cold climates. Blattner et al. (1997) also suggest that other studies where highly depleted ^{18}O values have been recorded (e.g., Bird and Chivas, 1988; Blattner and Williams, 1991) may also be indicative of meteoric waters sourced from glacial melts.

5.5. General circulation model simulations

A more recent approach to study Mesozoic climate has been through the application of GCM simulations of the ancient Earth. Such a methodology can provide an independent means of assessing global climate if data required to specify boundary conditions (e.g., palaeogeography, atmospheric CO_2, ocean temperatures) and to evaluate results, are kept independent to avoid circularity. Model simulations are now available for many different times, but the Mesozoic has been particularly popular (especially the Cretaceous).

Numerous GCM simulations are available for the Triassic (e.g., Kutzbach and Gallimore, 1989; Fawcett et al., 1994; Kutzbach, 1994; Wilson et al., 1994). These models, using elevated CO_2 concentrations (ranging from 1000 to 1650 ppm) and relief reaching a maximum of 2 km, provide results consistent with extreme temperature variability at polar latitudes. For example the model of Kutzbach (1994) simulated a mean annual temperature of $-5°C$, with winter temperatures of $-30°C$ and summer temperatures of 25°C over parts of Antarctica. The simulation of Wilson et al. (1994) produced summer temperatures of 20°C and winter temperatures dropping to a minimum of $-50°C$ over Antarctica and solid permafrost zone. Although a tract of sea-ice was simulated all year round, Wilson et al. (1994) considered the results to be inconsistent with polar ice sheet development.

In a GCM study of late Jurassic (Kimmeridgian–Tithonian) climate, Moore et al. (1992), using a thermodynamic slab ocean also simulated significant amounts of sea-ice. In their simulation using 280 ppm CO_2, the sea-ice front extended to 45°N in the northern hemisphere and 50°S in the southern hemisphere, whilst using 1120 ppm CO_2, the amount of sea-ice was significantly reduced, particularly in the southern hemisphere. Moore et al. (1992) considered the results to be consistent with both tillites being deposited on the margins of the Boreal and southern Austral seas and dropstones in adjacent marine sediments. A further GCM study of the late Jurassic climate showed also that permanent ice may be simulated over Antarctica as a result of Milankovitch (eccentricity-forced) orbital perturbations (Valdes et al., 1995).

In an early GCM simulation of mid-Cretaceous climate by Barron and Washington (1982), sea-surface temperatures were allowed to drop only to a minimum of 10°C and subsequently sub-freezing temperatures were predicted only on land. It is of note that in this GCM simulation when global temperatures were not fixed, sub-freezing mean annual temperatures extended down to $\sim 65°$ north and south and it is probable that extensive sea-ice would have formed (see also Ramstein et al., 1997). A simulation of early Jurassic climate by Chandler et al. (1992) where sea surface temperatures were fixed and likewise not permitted to drop below freezing, also produced seasonal sub-freezing temperatures only within the continental interiors. Winter temperatures in these areas dropped to $-31.9°C$ and the seasonal range exceeded 45°C over high-latitude mountains in northern Pangea, a range similar to the present day seasonality of Siberia (Chandler et al., 1992). Such temperatures may possibly be compatible with the formation of permanent or seasonal ice. However, such a large seasonal temperature range is not considered to be consistent with floral data (Ziegler et al., 1993) and may stem from the assumption that the atmospheric composition of the early Jurassic was the same as today.

More recent GCM simulations of the mid-Cretaceous by Barron et al. (1993; 1995) demonstrated that a combination of increased CO_2 in concert with changes in the oceanic heat transport resulted in significant polar warming, reduced temperature gradients and equatorial temperatures. However, sub-freezing temperatures in polar areas in this latter simulation still remain and hence the potential for the development of sea ice is still a possibility. Oglesby (1989), studying Antarctic glaciation using a GCM, also noted the great difficulty simulating conditions unfavourable for snow and ice accumulation, even under extreme imposed conditions. The model was unable to overcome the fundamental high-latitude obstacle of a long low-sun to no-sun season even with enhanced heating and thus Oglesby (1989) concluded that model results did not agree with the widely held interpretation of a predominately ice-free Antarctica, prior to 40 Ma.

The incentive for GCM analysis of mid-Cretaceous climate has often been to evaluate the extent to which such times provides an analogue for a greenhouse world and as such other possible cooler episodes recognised within the Mesozoic have received far less attention from a GCM perspective. Comparison of two GCM-generated predictions of mid-Cretaceous climate representing a greenhouse and an icehouse world has however, recently been completed by Price et al. (1998b). By comparison of greenhouse and icehouse palaeoclimates, Price et al. (1998b) were able to show how differences in processes, which are intrinsically linked with climate (such as continental weathering and snow and ice accumulation), may be translated into a recognisable sedimentary signature. An accumulation of ice at high latitudes was predicted in the icehouse simulation, which waxed and waned in concert with the seasons and could easily have resulted in metre-scale variations of sea level (as suggested by Valdes et al., 1995 for the late Jurassic). The icehouse simulation of Price et al. (1998b) predicts a permanent icecap on both poles and in the northern hemisphere these areas (Greenland and eastern Siberia) broadly duplicate the areas of highest relief. The total surface extent of the predicted permanent snow cover is approximately one third of that of the present day. Such a result was, however, hardly surprising with the imposition of the sub-freezing polar sea surface temperatures, based upon the results from Sellwood et al. (1994) as part of the model's boundary conditions.

6. Discussion

A wide variety of evidence including dropstones, deposits with affinities to glacial tillites, glendonite rich claystone sequences, in addition to perhaps more subtle or equivocal signals within the rock-record such as synchronous sea level changes, isotopic and faunal evidence has been used to infer that glacial conditions existed during the Mesozoic. Extensive floral evidence (e.g., Spicer and Parrish, 1986; Philippe and Thevenard, 1996; Parrish et al., 1998) also suggests that at times permanent ice at high altitudes and/or latitudes may have been present during the Jurassic and Cretaceous. For example with regard to the Australian region compelling evidence for glacial or at least seasonally sub-freezing conditions is provided by the occurrence of dropstones, glendonites, oxygen isotope ratios from well preserved biogenic carbonate material, cryoturbational structures and isotopic evidence for glacial meltwaters.

It appears central to the debate whether these supposed glacial deposits necessarily indicate the presence of a worldwide deterioration of climate and an ice-age or just localised freezing, 'a cold snap' or sub-freezing conditions at high latitude or altitude regions. Certainly the climatic conditions outlined for Australia during the early Cretaceous are consistent with at least seasonally sub-freezing temperatures (Constantine et al., 1998), perhaps interspersed with times when the prevailing climate deteriorated further leading to relatively short-lived ?Milankovitch scale glacial episodes. Such conditions may not necessarily be reflected in more temperate latitudes as it has been suggested that cold polar temperatures during the Mesozoic may have been very localised and did not affect lower latitudes to any great extent (Frakes et al., 1992). This would certainly seem likely if a steep pole-to-equator temperature gradient existed for such times (see below). Moreover, it has been suggested that an Antarctic ice cap could have persisted despite overall climatic warmth, because high sea surface temperatures enhance vapour transport to the centre of Antarctica, where temperatures may remain below freezing (Prentice and Mathews, 1991). The distribution of ice-derived sediments (Fig. 2a–c) suggest that they were generally confined to a region within a few degrees of the pole.

If the temperature regime of the Earth is such that the poles are normally below freezing for much of the year, there are still several other conditions which may be necessary to develop glacial conditions. The presence of a landmass at the poles (providing a site for the accumulation of snow) with high mountainous regions, the more likely is a glaciation. It is noteworthy, therefore, that a landmass on or adjacent to both poles throughout the Mesozoic was present (see Smith et al., 1994) and in an ice-free topographic reconstruction of Antarctica (Robin, 1988) places a large part of the continent above 1000 m during the Cretaceous. Vital climatic and environmental information supporting or countering glacial polar conditions may be present within the Antarctic continental interior, but is at present covered with ice.

The nature of the causes of the possible glacial events within the Mesozoic are likely to exert a strong influence upon the observed brevity of indicators within the rock-record. For example, if Milankovitch climate forcing (as suggested above) is a major factor causing minor glaciations to occur within essentially greenhouse states, such relatively short term cycles may not always be resolved from available time series climatic proxy data (see Valdes et al., 1995; Price et al., 1998b). Glacial and cold water sediments also tend to be reduced in thickness or absent due to being inextricably linked to glacio-eustatic hiatuses (Kemper, 1987).

There may also be a few non-climatic reasons as to why there is a general paucity of descriptions of glacial sediments and features of Mesozoic age. Although many suspected tills, dropstone laden deposits and other glacially derived sediments of Mesozoic age have been described, many of these early descriptions have not survived further tests of scrutiny and have subsequently been reinterpreted as being of non-glacial origin (see Hallam, 1993; Chumakov and Frakes, 1997). However, the recent renaissance in acceptance of cool or glacial climate episodes during the Mesozoic (e.g., Frakes and Francis, 1988; Weissert and Lini, 1991; Frakes et al., 1992; Sellwood et al., 1994; Stoll and Schrag, 1996; Constantine et al., 1998; Price et al., 1998a) has led to an increasing number of deposits, which may have been ascribed a non-glacial origin to be considered to have been deposited under at least seasonally sub-freezing temperatures. This is particularly the case for deposits within Australia. Siberia has been located at high palaeolatitudes (60–85°S) throughout the Mesozoic (Smith et al., 1994) and therefore should conceivably contain plentiful deposits of glacial origin if high latitude ice during this time was in existence. Data from this region does indicate ice, although many descriptions of possible tillites and dropstones await fuller description. The increasing number of investigations from this area may prove decisive if ice was a reality.

The possible duration of icehouse interludes within the Mesozoic can be seen in Fig. 3, which shows a semi-quantitative measure of the extent of the Earth's surface affected by glaciation or sub-freezing temperatures. The data shown implies a background deposition of glacially or sub-freezing derived sediments beginning in the late Triassic and extending through to the late Cretaceous. This pattern may be accounted for by a number of factors, including a 'smearing' of the ages of supposed glacial sediments resulting from the generally poorly dated nature of many of the deposits. Four major events are apparent, the Pliensbachian, Bajocian–Bathonian, Valanginian and Aptian, indicated by sharp increases in both glendonites and deposits with affinities to glacial tillites and dropstones. Only during the Tithonian/Volgian stage there is a marked increase in glacial tillites and dropstones which is not accompanied by glendonites. It must be recognised, as noted above, that many of these deposits are frequently poorly biostratigraphically constrained, and this is particularly true with respect to the early Jurassic. If these four or five events are truly indicative of glacial conditions, it may be considered that the background resulted from isolated mountain glaciers or shore ice, when polar ice receded. Kemper (1987) proposed that cold periods within the Mesozoic lasted from a few thousand to 2 Ma in length and were separated by periods of warm equable climate. Likewise, Weissert and Lini (1991) propose that the

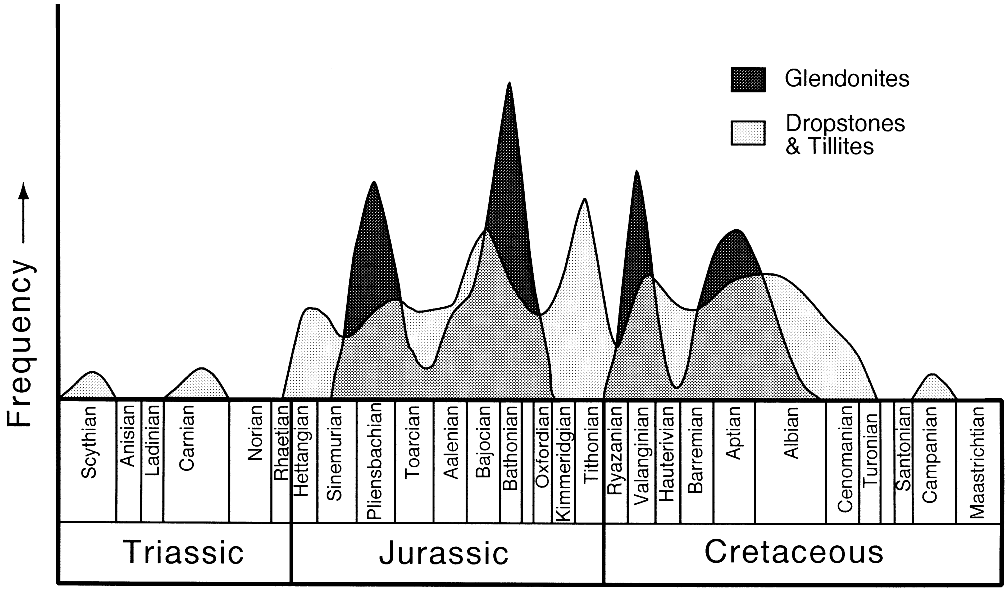

Fig. 3. The distribution of possible glacially derived sediments and glendonites through the Mesozoic. A semi-quantitative measure of the extent of the Earth's surface affected is indicated by the heights of the peaks. Data derived from references cited within the text.

cooling event around the Aptian–early Albian boundary lasted up to a few 10^5 years.

The implied synchronous changes of the Haq et al. (1987) eustatic sea level curve requires significant amounts of ice, not just small isolated mountain ice sheets that today represent $<3\%$ of the total grounded ice volume (Rowley and Markwick, 1992). Further, if taken at face value, each of the large regressive episodes should correspond to a glacial event, which is undoubtedly unjustifiable, particularly with respect to the scant data indicating glacial conditions in the Triassic compared with the observed sea level fluctuations. If, however, the possible glacial or sub-freezing events, outlined above, do correspond at least in part to major sea level falls this would provide some support that these particular regressions may be of a truly global nature. The Haq et al. (1987) sea level curve is shown in Fig. 4. Major regressional events occur during the Bathonian, Tithonian, Valanginian and Aptian which lends some credence to fluctuating polar ice volumes as a primary mechanism causing *these* sea level changes. Conversely, a transgressional and not a regressive episode occurs within the Pliensbachian-outlined as a possible candidate for a glacial interlude. As noted above, because of the interplay between eustasy, subsidence and accommodation space, sediments deposited in transgressional episodes are more likely to be preserved and hence the sedimentary record for the Pliensbachian is potentially being biased towards a glacial scenario. Furthermore, the sedimentary evidence for the early Jurassic is possibly the most poorly constrained. Some of the regressional events of Haq et al. (1987), particularly in the Tithonian, Valanginian and Aptian show a reasonable degree of support from a number of other facies and stratigraphic studies in different parts of the world (see Hallam, 1992 and references therein; Sahagian et al., 1996). The study of Sahagian et al. (1996) is particularly germane as this analysis of sea level change was carried out on the relatively tectonically quiescent Russian Platform and in Siberia, upon which many of the possible glacially-derived sediments are located (see Fig. 2b–c).

Also shown in Fig. 4 is an estimate of humidity–aridity (based upon clay mineral abundances) in Europe through the Mesozoic. Conventional wisdom suggests that glacial episodes are associated with periods of aridity, partly due to the huge volumes of water being locked-up in the polar icecaps. Price et al. (1998b), who investigated, through GCMs, icehouse interludes of the mid-Cretaceous suggested,

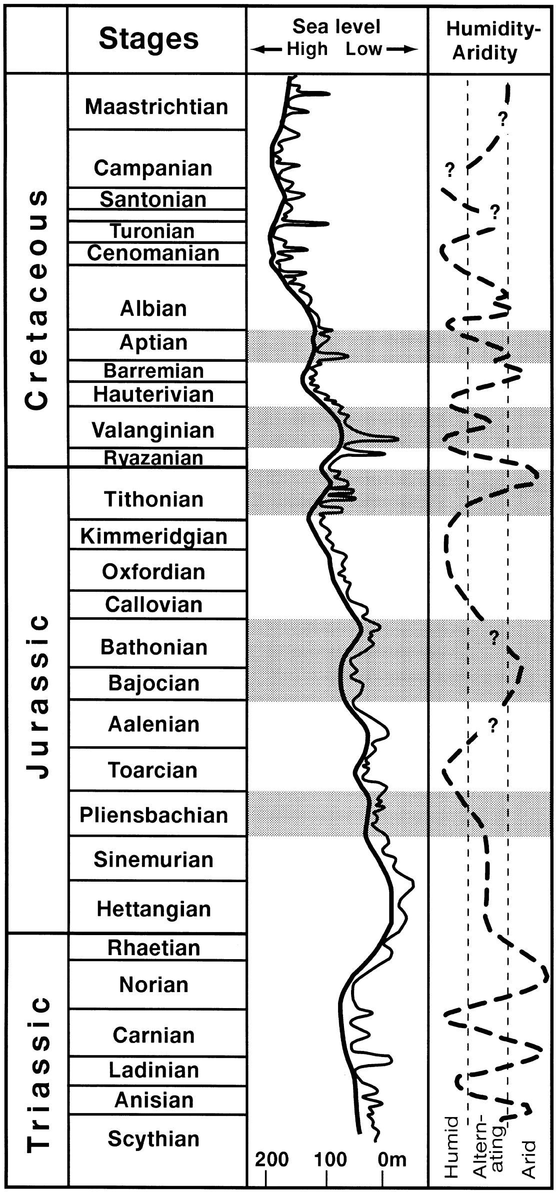

Fig. 4. Sea level and aridity–humidity cycles during the Mesozoic. Global sea level variation is taken from Haq et al. (1987), clay mineral change in Europe from Ruffell and Batten (1990), Simms and Ruffell (1990), Hallam et al. (1991) and A.H. Ruffell (pers. commun.).

however, that the climate at low latitudes in the icehouse simulation was generally moister than a warmer greenhouse simulation, which could affect weathering regimes and result in deposition of kaolinite-dominated clay suites. Mid-latitudes in the icehouse simulation of Price et al. (1998b) were, however, notably more arid than that of the greenhouse simulation and could be expected to result in the deposition of smectite-dominated clay suites. If the above reasoning is correct then the glacial episodes identified in Fig. 3 should correspond to the episodes of aridity in Europe. The fact that they do imparts further confidence that these episodes in the Jurassic and early Cretaceous are cool or glacial events. The general lack of reported glacially-derived deposits of Triassic age (Figs. 1 and 3) appears to be in conflict with the above arguments as this period has widespread sedimentary indicators of aridity. However, it may be argued that the observed aridity of the Triassic might be related to the continentality of the Pangea landmass (e.g., Parrish et al., 1982), whilst the aridity maintained after continental break-up (which intuitively should be decreasing), during the Jurassic and Cretaceous, may in part be related to icehouse interludes. GCM simulations of Triassic climate are suggestive of extreme high-latitude temperature variation consistent with large-scale continental aridity and also ice-free polar regions (Wilson et al., 1994).

The studies by Crame (1986; 1993) identified marked bipolarity in the distribution of certain bivalves during the Jurassic (Pliensbachian and Tithonian) and early Cretaceous (Aptian–Albian). Further, there is also evidence that certain bivalves may have had a bipolar distribution during the mid-Jurassic (Crampton, 1988; Crame, 1993). It may not be just coincidence that these periods of time correspond to the episodes outlined in Fig. 3 where possible glacial sediments and glendonites are most abundant. A mechanism for the formation of bipolar taxa exists whereby separation occurs when the Earth's pole–equator temperature profile increases, causing the expulsion of taxon from equatorial regions (see Crame, 1993). Thus, low faunal provinciality is often equated with equable climates when the pole–equator temperature profile is significantly reduced and accordingly environmental and climatic differences between high and low latitudes are significantly diminished. A relationship between strong bipolarity and glacial polar conditions does not necessarily imply a sole temperature control which remains in doubt (e.g., Hallam, 1984, 1994), but may be additionally related to other factors associated with polar climates including seasonality of temperature, salinity variation and prolonged periods of darkness. Hence during more equable times, although polar temperatures may have increased, these latter factors may still have been prevalent and therefore still promoting provinciality. It is possible that although these episodes of increased bipolarity may be associated with the proposed glacial episodes outlined in Fig. 4 they are also often coincident with sea level lows which in turn can also promote endemism and provinciality (Hallam, 1994; Cecca, 1999).

The proposition that glacial conditions existed during the Mesozoic, is not new (e.g., Woolnough and David, 1926; Double, 1931; Gunn and Warren, 1962) and has long been vigorously debated (e.g., Hawkes, 1951; Borns and Hall, 1969; Ballance and Watters, 1971), whilst the era representing a time of prolonged warmth has developed and become widely accepted. Evidence for high-latitude warmth during Mesozoic intervals is abundant, and in addition to the poleward expansion of organisms such as larger foraminifera, dinosaurs and floral evidence (e.g., Ziegler et al., 1993; Herman and Spicer, 1997) outlined above, includes the occurrence of coral reefs, widespread bauxites, coals and kaolinite-rich paleosols at temperate and polar regions (see Hallam, 1975; Frakes, 1979; Parrish et al., 1982; Barron, 1983; Chandler et al., 1992; Price et al., 1997; Retallack and Alonso-Zarza, 1998).

There are several hypotheses proposed to account for Mesozoic warmth which are unlikely to be exclusive, including a redistribution of energy about the planet's surface, changes in palaeogeography, a net change in the amount of energy trapped by the atmosphere and the amount of energy received by the Earth. Barron and Washington (1984; 1985) estimated that the mid-Cretaceous continental configuration alone would produce an average global warming of 4.8°C above present day values, a high latitude warming of 10°C and a further rise in global temperatures of 3.6°C could be achieved by a combination of both palaeogeographic effects and a higher (four times present-day levels, see Berner, 1994) atmospheric CO_2 content. According to Berner (1994), during much of the Mesozoic CO_2 concentrations were maintained consistently above four times present-day values (although the absolute estimates are known only to within a factor of three). CO_2 releases associated with a mid-Cretaceous super plume and the emplacement of the Ontong–Java Plateau have been suggested as a principal cause of the mid-Cretaceous global warming (Caldeira and Rampino, 1991). A pulse in ocean crust production occurring between 120 and 100 Ma, primarily in the Pacific, is associated with episodes of increased mantle outgassing, especially of carbon and nutrients (Larson, 1991). A combination of decreasing mantle activities and a lowering of atmospheric CO_2, the formation and uplift of the Himalayas and the Tibetan Plateau may have been responsible for the Cretaceous–Cainozoic cooling trend (Frakes et al., 1992; Raymo and Ruddiman, 1992; Caldeira et al., 1993; Berner, 1994). Significantly a recent high-resolution study of atmospheric CO_2 variation over the last 150 Ma by Tajika (1998) suggests that observed drops in CO_2 levels are coincident with the inferred early Cretaceous cool episode of Frakes et al. (1992). Weissert and Lini (1991) also suggest that cooling events in the early Cretaceous, could have been triggered by lowering of atmospheric CO_2 and invoke a mechanism of accelerated extraction combined with a decrease transfer of external volcanogenic CO_2 into the atmosphere. Likewise, Oyarzun et al. (1999) suggest that the middle Carboniferous and early Permian icehouse and earliest Permian and mid-Permian–Triassic greenhouse climates were primarily related to uplift, erosion and CO_2 export from the atmosphere and extension and volcanism, respectively. It may be postulated that such mechanisms may also be responsible or influence the icehouse–greenhouse fluctuations of climate suggested for the Jurassic and Cretaceous.

Hypotheses concerning redistribution of energy mostly invoke changes in the locations of ocean gateways and continents and strengths of oceans currents as a means of altering the global heat distribution (e.g., Covey and Barron, 1988; Rind and Chandler, 1991; Barron et al., 1993; Sellwood et al., 1994). Estimates for parts of the Cretaceous have suggested that tropical sea surface temperatures were lower (Sellwood et al., 1994; D'Hondt and Arthur, 1996) or no warmer than today (Wilson and Opdyke, 1996) despite being under greenhouse conditions. Such temperatures have been used to suggest that equator-to-pole temperatures gradients were much lower (more equable) and hence meridional heat transport was much greater for these times resulting in increased polar warming. Rind and Chandler (1991) demonstrated that a 15% increase in ocean poleward heat transport provides sufficient high-latitude energy convergence to remove sea ice and provide a global climate 2°C warmer than the present-day control experiment. By inference, therefore, a reduction in poleward heat transport could potentially promote glacial conditions at the poles. A possible scenario could be envisaged in possible Mesozoic glacial times where in an absence of poleward heat transport, effectively removing heat from the tropics, the tropical regions were consequently as warm or warmer than they are today. Thus paradoxically, evidence for cold or sub-freezing Mesozoic polar climates might potentially be gathered from tropical latitudes. It is of note that, based upon GCM experiments, Rind (1998) suggests that such a temperature gradient (where there is little change compared with today) in addition to warm tropical–sub tropical conditions should be expected to produce aridity in these areas, confirming concepts outlined above. The possibility of a reduction in ocean heat transport as a primary mechanism to bring about ocean cooling and initiation of polar ice growth is however, uncertain. Changes in heat transport in the modern Atlantic ocean, for example, are controlled in effect by the growth of sea ice (as opposed to the other way around) and/or cooling and freshening of the North Atlantic due to meltwater influxes which may in turn be controlled by a combination of Milankovitch induced climatic perturbations and CO_2 variations (see Broecker et al., 1985; Rind and Chandler, 1991).

7. Conclusions

The Mesozoic, perhaps representing the longest period of warmth during Phanerozoic Earth history, contains in general a paucity of direct evidence for polar ice. The origin of certain deposits (e.g., dropstones and glendonites) is still highly debated (e.g., Frakes et al., 1995; Markwick and Rowley, 1998; Frakes, 1999 cf. Bennett and Doyle, 1996). More equivocal indicators of glacial or cold polar conditions, such as faunal and floral data, oxygen and carbon isotope stratigraphies and sedimentological evidence for global sea level change provides further methods of examining the possible glacial history of the Mesozoic. Because of the inherent equivocal nature of these latter lines of evidence it is suggested that it would be unwise to interpret them in isolation.

Four episodes (Bajocian–Bathonian, Tithonian/Volgian, Valanginian and Aptian) or conceivably five (if the Pliensbachian is included) of cold or sub-freezing polar climates are recognised. The longevity of these events may be represented by a 'cold snap' or longer periods within a stage, although undoubtedly the possible 'smearing' of ages may have had the effect of lengthening and hence promoting the importance of these proposed events. The climate regime of the Earth during these times may be hypothesised to be characterised by a relatively steep pole-to-equator temperature gradient where low-latitude regions are as warm or warmer than today. The evidence to support such reasoning includes sharp increases in both glendonites and deposits with affinities to glacial tillites and dropstones for these times. That there exists also a coincidence of sea level drops, arid events and an increased bipolarity of faunas at these times imparts further confidence that these are events, which were of a magnitude to effect the Earth as a whole. The development of ice sheets requires a global cooling and it is suggested that there was a contribution from a marked decrease in atmospheric CO_2 (see also Frakes et al., 1992), although considerable debate relating to the interplay between mantle activities, volcanogenic CO_2 input, tectonic uplift, erosion and CO_2 export from the atmosphere remains (e.g., Raymo and Ruddiman, 1992; Caldeira et al., 1993; Berner, 1994).

The general clustering of evidence at very high palaeolatitudes suggests that the extent of polar ice during the Mesozoic is unlikely to have reached Pleistocene glacial maximum conditions. An ice cap approximately one third the size of the present day has been advocated (e.g., Price et al., 1998a) which was largely restricted to continental interiors possibly leaving coastal areas seasonally ice free. Through the analysis of GCM simulation results (e.g., Oglesby, 1989; Wilson et al., 1994; Barron et al., 1995; Valdes et al., 1995; Ramstein et al., 1997) a very large seasonal temperature cycle in polar regions with at least winter cooling appears to be an inescapable feature of Mesozoic climates. GCMs appear unable to overcome the fundamental high-latitude obstacle of a long low-sun to no-sun season (Oglesby, 1989), even under conditions of high CO_2 and increased oceanic poleward heat transport, and hence such modelling studies are potentially faced with the problem of justifying the presence, rather than absence of frigid polar conditions.

If such an ice cap were to wax and wane, it is envisaged it could still not account for the large sea level fluctuations advocated by Haq et al. (1987) which implies a world in which ice, in the form of large continental ice sheets has played a significant if not dominant role. However, changes in ice volume coupled with Milankovitch climate-induced changes in ground water storage (e.g., Hay and Leslie, 1990; Jacobs and Sahagian, 1993) could have the potential to come close to producing the albeit conjectural synchronous eustatic changes in sea level. It may, therefore, be postulated that the times of cold or sub-freezing polar climates outlined above could represent globally synchronous events and being reflected in the sea level curves.

Glacial conditions do not unfortunately leave an indelible hallmark upon the Earth but instead frequently circumstantial evidence only, although the absence of evidence is not necessarily evidence of absence. It must be remembered that throughout the Mesozoic high-latitude warmth is in fact the norm, although limited polar ice at times is not a myth but instead is a reality.

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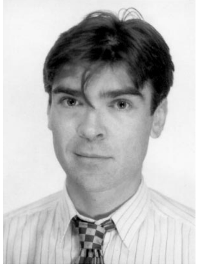

Gregory Price obtained a BSc (Geography and Geology) degree from the West London Institute of Higher Education in 1988. Afterwards he spent a short period of time working for British Petroleum in London, before completing his masteral (Sedimentology and its Applications in 1990), and doctoral studies (1994) looking at aspects of paleoclimate modelling in the Mesozoic at the Postgraduate Research Institute for Sedimentology, University of Reading. He subsequently continued research into climate change and Mesozoic palaeoclimates at the School of Geosciences, Queen's University of Belfast. In particular his research focused upon isotopic and trace element variation in modern bivalves and reconstruction of Pliocene climates together with an examination of the timing and causes of Jurassic and Cretaceous greenhouse and icehouse episodes. In 1998 Gregory joined the Department of Geological Sciences, University of Plymouth as a Lecturer in Environmental Sedimentology, where in collaboration with colleagues from the UK, Germany and Russia he is continuing research particularly relating to Jurassic–Cretaceous climate change in the UK and the Volga basin, Russia.