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SPECIAL

Oceanic gateways as a critical factor to initiate icehouse Earth

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We propose a unifying explanation for the four major icehouses during the past *c*.620 million years: earliest Oligocene to Present; early Carboniferous to early Permian; late Ordovician and late Vendian (the 'snowball Earth') all of which appear to have been initiated as a result of two plate-tectonic processes. The first moved some continents into polar latitudes; while there the second process opened and closed oceanic low latitude gateways that changed global oceanic circulation from one with important circum-equatorial currents (greenhouse) to one with inhibited circum-equatorial deep-water currents (icehouse) and more restricted oceanic gyres.

Keywords: Icehouse, glaciations, greenhouse, oceanic gateways.

In the Phanerozoic era—the last 545 million years (Gradstein & Ogg 1996)—there have been three major icehouse periods (Fischer 1981): the earliest Oligocene to Recent early Carboniferous to early Permian and late Ordovician (Fig. 1). They have a total duration of less than 120 million years. Minor glaciations may also have taken place in the earlier Ordovician early Silurian and late Devonian (Eyles 1993; Crowell 1999). A fourth major icehouse period occurred in the Vendian and has given rise to the notion of a 'snowball Earth' (Kirschvink 1992). All four icehouses developed when one or both geographic poles lay within or less than 1000 km from a large continent but there have been periods when a polar continent such as Antarctica during much of the Cretaceous greenhouse world has not been glaciated (Smith *et al.* 1994). Thus a polar or sub-polar position for a continent appears to be a necessary condition but is not a sufficient pre-condition for widespread glaciation. High topography has also been invoked as an important factor (Eyles 1993).

Cenozoic icehouse. Although there is a $\delta^{18}O$ minimum at 53 Ma (Stott & Kennett 1990) the oxygen isotope data acting as a proxy for ice volume together with plate-tectonic reconstructions (Fig. 2a) suggest that the onset of the present icehouse world started at 36.5 Ma principally by the opening of the Tasmanian gateway (Exon *et al.* 2000; Carter *et al.* 1996). The separation of Australia from Antarctica allowed cool surface currents to develop leading to the development of the Antarctic ice sheet. Geochemical proxies suggest that by 32.8 Ma the Drake Passage between South America and Antarctica was open to intermediate and deep water circulation (Latimer & Filipelli 2002) rather than at *c*.23 Ma (Lawver *et al.* 1992; Exon *et al.* 2000). The opening of this gateway eventually led to the relative thermal isolation of Antarctica and the creation of the clockwise strong Antarctic circumpolar current. Antarctic ice sheets comparable to those of the present-day date from *c*.15 Ma (Shackleton & Kennett 1975; Kennett 1977) as does the probable initiation of North Atlantic Deep Water production (Marjoran & Pringle 2001; Piotrowski *et al.* 2000). Some of these changes have been linked to the partial closure of the gateway at the Isthmus of Panama (Roth *et al.* 2000) or changes in the topography of the Greenland–Scotland Ridge (Wright & Miller 1996). The initiation of the North polar ice cap has been linked to the complete closure of this gateway between 4.5 and 2.6 Ma (Coates 1992; Farrell 1995; Droxler *et al.* 1998) which stopped the equatorial interchange of Pacific and Atlantic deep water (Droxler *et al.* 1998). The effect of the closure was to force warm water into the North Atlantic leading to increased production of North Atlantic Deep Water (Warren 1983; Marjoran & Pringle 2001) and/or expansion of the East Antarctic ice sheet (Marjoran & Pringle 2001). It also led to the formation of an ice-cap in the Northern Hemisphere at *c*.2.75 Ma (Haug *et al.* 1999; Cane & Molnar 1999) to *c*.2.5 Ma (Shackleton *et al.* 1984). The step-wise deterioration in global climate was signalled by an overall positive isotope excursion in the $\delta^{18}O$ record of *c*.2‰ (PDB scale) from the earliest Oligocene to the Last Glacial Maximum (Miller *et al.* 1987).

Permo-Carboniferous icehouse. Ice existed on Gondwana throughout the Carboniferous Period from the Tournaisian at about 354 Ma and continued to about mid-early Permian time at about 369 Ma (Gonzalez-Bonorino & Eyles 1995) a duration of 85 million years. Small areas of ice may have existed in Late Devonian time at *c*.375 Ma. The extent of the Tournaisian to Visean glaciation was limited to isolated with relatively small ice centres but a more than five-fold increase took place at about the Visean–Namurian boundary *c*.327 Ma leading to maximum cover during most of the Namurian (327 to *c*.317 Ma) and early Westphalian. The ice gradually decreased throughout the late Carboniferous eventually leading to isolated ice centres that covered a larger area than did the early Carboniferous ice centres. As with the Cenozoic glaciations the Permo-Carboniferous continental ice sheets are associated with a positive isotope excursion in the $\delta^{18}O$ record of *c*.3‰ (PDB scale) (Mii *et al.* 1999).

All palaeocontinental reconstructions based on selection of the available palaeomagnetic data spanning the Devonian to early Carboniferous interval show that southern Laurussia and northern Gondwana (in palaeo-coordinates) have similar latitudinal ranges (Fig. 2b). Their relative longitudes are unknown until they have finished colliding but within the limits of error an oceanic gateway could have existed in sub-tropical latitudes between the two supercontinents at any time in the early Devonian to late Carboniferous interval. The geological evidence is more precise for that part of Europe adjacent to Gondwana: a narrow oceanic seaway is depicted in Givetian–late Middle Devonian time 380–370 Ma which had been closed by the Fammenian–latest Devonian time 364–354 Ma (Ziegler 1989). Closure would have shut down the subtropical ocean current between the two continents. While concurrent topographic changes may have modulated the ice volume other gateways such as those that may have formed

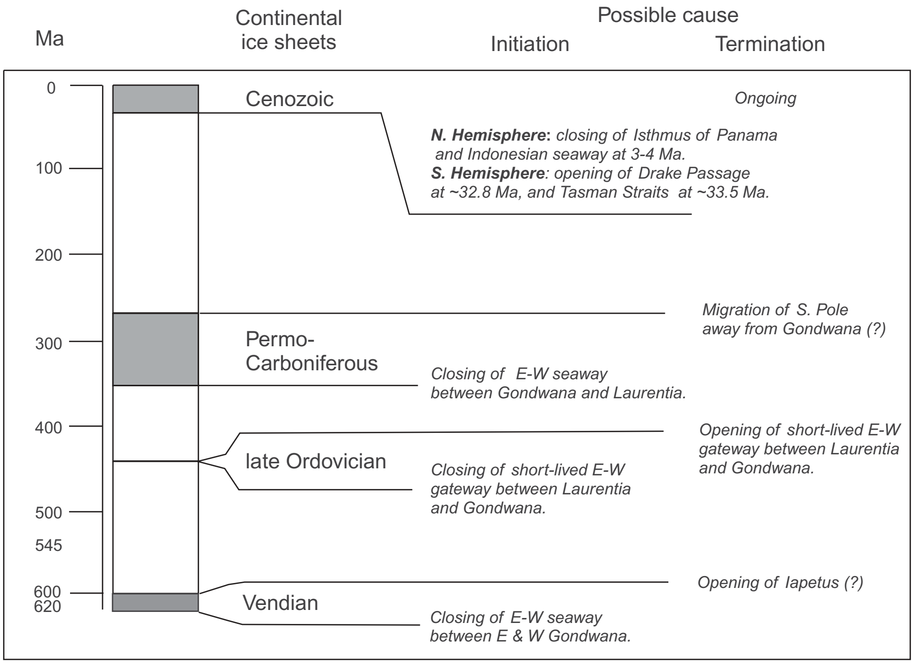

Fig. 1. Durations of the main continental ice sheets for the past 620 million years showing possible causes for their initiation and termination with the geological time scale of Gradstein & Ogg (1996).

during the complex evolution of the Altaids of present-day central Asia Şengör & Natal'in 1996) could have brought about stepwise changes in the climate of polar Gondwana.

Late Ordovician icehouse. In Late Ordovician time (Hirnantian stage of the Ashgill *c.*443–444 Ma) a major short-lived glaciation affected western Gondwana (mostly NW Africa) (Fig. 2c). The ice age may have lasted for only 1 million years or possibly as little as 0.5 million years (Brenchley *et al.* 1994) although this icehouse period may have lasted 4–6 million years beginning in the Caradoc with peak glaciation during the Hirnantian stage of the Ashgill (Pope & Steffen 2001). Stable-isotope data from brachiopods shows a dramatic positive isotope excursion in the δ^{13}C and δ^{18}O record (PDB scale *c.*2‰) for eastern North America central Sweden and the Baltic States. In the Baltic States the magnitude of these isotopic excursions is up to *c.*4‰ equivalent to the combined effects of a sea-level fall of 100 m and a drop of 10 °C in tropical sea surface temperatures.

Why this icehouse came into being in the middle of a greenhouse period and then lasted for such a short time has always been a puzzle. We suggest here that its initiation and demise are attributable to the action of a Central American or similar gateway noted above (Fig. 2c). The palaeomagnetic data suggest that NW Gondwana and SW Laurentia were closer to one another at 440 Ma than they were just before or just after the icehouse (cf. Pickering & Smith 1995). Thus there was a potential gateway of the correct age; it could have closed in the late Ordovician and could have re-opened shortly afterwards. Plate tectonic motions have the appropriate time- and length-scales for what is required: about 100 km in about 1 million years.

Late Precambrian icehouse. The late Precambrian Vendian icehouse—600–620 Ma—'Varangerian' or 'Marinoan' is the least well known and most poorly dated of the four icehouses and has given rise to the greatest controversy (Evans 2000). This glacial epoch was preceded by pronounced δ^{13}C enrichment in surface seawater giving rise to high δ^{13}C values (Kaufman *et al.* 1997). In some sections these high values declined to more moderate values just below the glacial deposits. Like those of the late Ordovician icehouse (Brenchley *et al.* 1994) the high δ^{13}C values have been interpreted as indicating high rates of organic production and burial followed by a reduced atmospheric CO_2 causing a smaller greenhouse effect that led to icehouse (Kaufman *et al.* 1997).

The 600 Ma reconstruction (Fig. 2d) is an interpolation between two recent tentative reconstructions at 580 and 620 Ma (Smith 2001). The 620–580 Ma represents the interval during which west and east Gondwana probably collided to form the supercontinent. Before collision a seaway separated the two halves of Gondwana which was then removed. Figure 2d shows that the seaway was approximately equatorial. It is speculated that its closure induced the same sequence of events postulated above for the initiation of the Permo-Carboniferous and late Ordovician ice ages: disruption of the pre-existing oceanic circulation and refrigeration of the south polar region.

When allowance is made for the uncertainties in the tectonics the palaeomagnetic pole positions and the ages of the glaciogenic deposits the important features of the Vendian map are similar to those of the mid-Carboniferous (Fig. 2b and d). However the Vendian icehouse is regarded as the prime example of the 'snowball Earth' (Hoffman *et al.* 1998) an hypothesis that arose because some apparently reliable palaeomagnetic data from Vendian glacial deposits placed them near the equator (Harland 1964; Kirschvink 1992). It was speculated that the whole Earth had been simultaneously glaciated a view discussed in detail by Evans (2000). Leather *et al.* (2002) conclude that the Neoproterozoic glacials of Oman record oscillatory glaciations similar to those of the Pleistocene and do not support prolonged shutdown of the hydrological cycle required by a snowball Earth.

Discussion. In the Cenozoic the only agreed mechanism for bringing about the successive step-wise deteriorations in global climate that led to the establishment of continent-wide ice-sheets is the opening of high-latitude gateways and the closing of sub-tropical gateways although the effects of each gateway are not

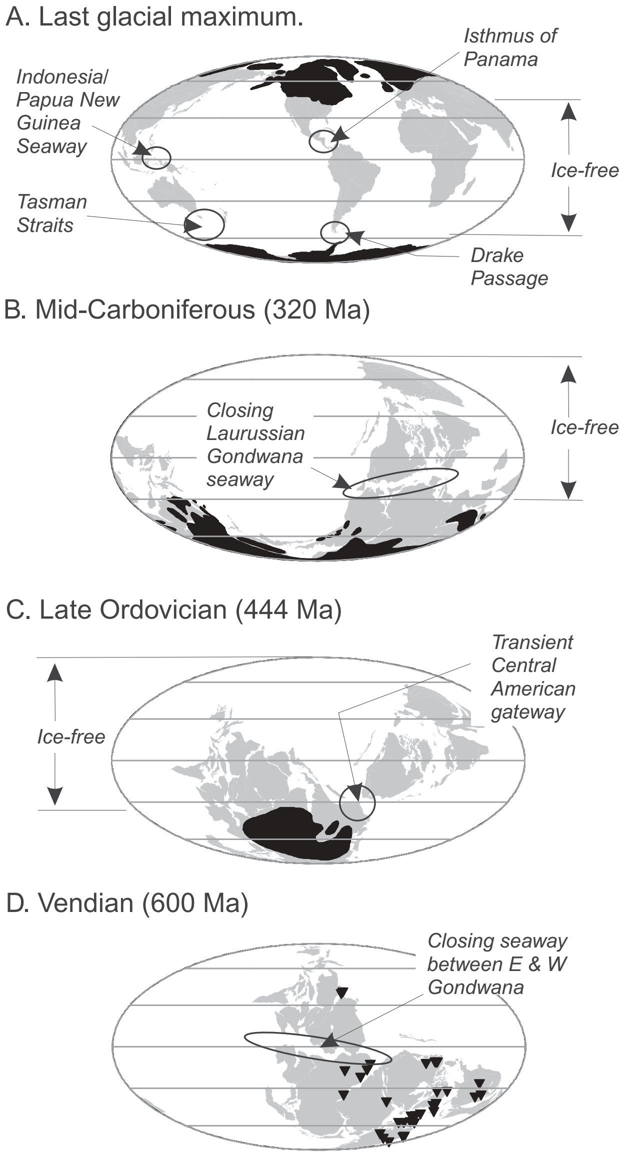

Fig. 2. All maps are Mollweide projections. (**a**) The present-day world. (**b**–**d**) Projections of the continental masses onto a global map frame using estimates of their mean palaeomagnetic poles as the projection pole. Latitude lines are drawn at intervals of 30°. (**a**) High-latitude Cenozoic gateways that have opened are the Drake Passage and the Tasman Straits; equatorial gateways that have closed are the Isthmus of Panama and the seaway between Indonesia and Papua New Guinea. The black areas are estimates of the ice cover at the last glacial maximum (Peltier 1994). (**b**) The reconstruction for mid-Carboniferous time (320 Ma) shows the location of a major seaway between Laurussia and Gondwana which closed when the supercontinents collided to form Pangaea. The closure is believed to have initiated the glaciation. The palaeomagnetic data show that a gateway could have closed this seaway at any time from early Devonian time onwards but the longitudinal uncertainty and the errors make it impossible to be precise about its location and age. The black areas are estimates of ice cover for the entire Permo-Carboniferous glaciation (Smith 1997) based mostly on Eyles (1993). In detail successive glaciations can be recognised (Gonzalez-Bonorino & Eyles 1995). The ice in Australia is of late Carboniferous to Permian age; its low latitude simply reflects its position on a mid-Carboniferous map. (**c**) The reconstruction is for late Ordovician time (444 Ma) modified slightly from Smith (1997). If Laurentia and Gondwana are brought into contact by sliding one or other supercontinent along palaeolatitude lines then NW South America joins central America. The two continents are further apart before and after this time suggesting that an open gateway could have existed here just before and just after 444 Ma. The closure at 444 Ma might have caused effects analogous to the closing of the Isthmus of Panama changing the oceanic circulation in such a way as to initiate an ice cap which melted once the gateway opened a million years later. The black areas are estimates of ice cover taken from Smith (1997). (**d**) The Vendian map at 600 Ma is a modification of the tentative reconstructions at 580 and 620 Ma of Smith (2001). One of the main tectonic events in progress at this time is the collision of West and East Gondwana. The collision eliminated a major east-trending tropical seaway and may have initiated ice sheet formation as suggested for the Permo-Carboniferous ice age. Inverted triangles are locations of all glaciogenic deposits on Gondwana Laurentia Baltica and Siberia that have generally been assigned to the younger Neoproterozoic (Vendian) glaciation—'Varangerian' or 'Marinoan' although many age assignments have very large uncertainties (Evans 2000). Ice persisted (or reappeared) locally because Cambrian glaciogenic deposits are known from West Africa (Evans 2000).

intuitively obvious. It is therefore surprising that a similar explanation has not been proposed for pre-Cenozoic icehouse periods. We argue that the early stages of opening and closing of appropriate oceanic gateways provides a plausible testable mechanism for the initiation and demise of the Permo-Carboniferous Ordovician and Vendian icehouses. During icehouse periods the distribution of continents inhibited circum-equatorial circulation forcing faster oceanic circulation in the main ocean gyres (Gerhard & Harison 2001; Pickering & Smith 2001). However whether the increased circulation leads to increased snow and ice accumulation in high-latitude regions depends in part on the strength of the contemporaneous circum-polar circulation. The problem is complex and requires numerical modelling for its solution. However in our view once the global ocean circulation had changed all the isotopic effects followed. We believe that pCO_2 Milankovitch-beat and other processes became significant in driving glacial–interglacial events only after the continental configurations gateways and associated ocean gyres were established. There is no need to appeal to solar luminosity variations intense volcanic activity (Chumakov 2001), or in the case of the snowball Earth extreme solutions such as changes in obliquity, true polar wander and non-dipole fields. If gateways have been of fundamental importance in initiating these icehouses the interesting question is why there are no glacial deposits in the 2200–950 Ma interval (Crowell 1999).

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