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The Antarctic palaeo record and its role in improving predictions of future Antarctic Ice Sheet change

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Abstract
This paper reviews the ways in which the palaeo record of Antarctic ice sheet change can be used to improve understanding of contemporary ice sheet behaviour, and thus enhance predictions of future sea-level change. The main areas where the palaeo ice sheet record can contribute are understanding long-term ice sheet trajectory; providing data against which ice sheet models can be tested; to identify and understand the range and types of natural ice sheet behaviour; to balance the global water budget; to correct contemporary glaciological measurements of mass change; and to understand the relationship between polar ecosystems and the ice sheet. I review each in turn and argue that research priorities include understanding past West Antarctic Ice Sheet collapse and its timing; a focus on the palaeo record of rapid retreat events and how these unfolded in the geological past; improving the number and range of ice sheet reconstructions, particularly through the Holocene; continuing to investigate the potential for using sediments and landforms to parameterise basal conditions in ice sheet models; and understanding past East Antarctic Ice Sheet dynamics, particularly the evidence for partial deglaciation.

1. Introduction

The most recent Intergovernmental Panel on Climate Change (IPCC) report recognised the importance of the palaeo record for understanding contemporary and future climate and sea-level change. The aim of this paper is to examine the palaeo record of the Antarctic ice sheet under a number of themes where it can inform the sea-level debate. For each, I explain the importance, and then give a personal view of progress to date and future prospects.

The motivation behind much palaeoenvironmental research is to improve our understanding of natural variability and provide a long-term context for recent and contemporary environmental changes. The 4th IPCC Assessment report (IPCC, 2007) stated that, "*Palaeoclimate science has made significant advances since the 1970s…….understanding is much improved, more quantitative and better integrated with respect to observations and modelling*." However, the IPCC also noted that "*Because understanding of some important effects driving sea-level rise is too limited, this report does not assess the likelihood, nor provide a best estimate or an upper bound for sea-level rise*", and more specifically in the case of Antarctica and Greenland "*The sea-level projections do not include ……the full effects of changes in ice sheet flow, because a basis in published literature is lacking.*".

The uncertainty in ice sheet dynamics has been well known in glaciological circles where modellers have faced a significant challenge in 'catching up' with some surprising field observations, such as the rapid movement of water under ice sheets (e.g. Zwally *et al.*, 2002; Gray *et al.*, 2005; Wingham *et al.* 2006), rapid thinning, retreat and acceleration of outlet glaciers (e.g. Rignot *et al.*, 1998; Shepherd *et al.*, 2001; Thomas *et al.*, 2004), rapid collapse of Antarctic ice shelves and a consequent acceleration in feeder glaciers (e.g. de Angelis and Skvarca, 2003; Scambos *et al.*, 2004; Rignot *et al.*, 2004).

A significant recent advance in modelling has been the development by Schoof (2007a; 2007b) of a practical solution to the problem of modelling grounding-line dynamics, which has previously hampered models trying to simulate a marine ice sheet such as the West Antarctic Ice Sheet (WAIS) (e.g. Vieli and Payne, 2005) (Fig. 1). So it could be argued that armed with important new observations of behaviour, a major stimulus from the IPCC, and a key development in modelling technology the community is well-placed for a 'big push' on modelling, where a major investment in ice sheet modelling could result in substantially improved predictions of future sea-level rise.

The question for this paper is how has the palaeo community contributed to improved predictions of Antarctic Ice Sheet change, and where are further contributions to understanding future sea-level rise likely to emerge?

1.1. The importance of Antarctica

The key role of the Antarctic ice sheets in sea-level change is well-rehearsed. The crux of the problem is that the WAIS rests on rock below sea-level (i.e. it is a marine ice sheet), and is grounded for much of its margin on a reverse slope (slope is downward from the margin to the interior). This configuration has long been thought to be inherently unstable (Weertman, 1974; Mercer, 1978): a marine ice sheet is only grounded because of the thickness of ice above flotation so any changes that reduce ice thickness can potentially cause flotation of the ice sheet edge (Fig. 2). With a reverse slope such a change can be introduced by grounding line retreat, which leads to thicker ice at the grounding line, increased stress with consequent flow acceleration and thinning. This leads to further grounding line retreat which can create a "runaway" feedback which continues until the grounding line encounters a forward slope. So the potential exists for a large and rapid contribution to sea-level change by instability in the WAIS which contains enough ice to raise sea-levels by 5 m (Lythe *et al.*, 2001). Vaughan (2008) provides a comprehensive review of the concept of WAIS instability, and the ways in which it has driven glaciological research for more than three decades.

The last decade or so has witnessed a number of key measurements, particularly from the Amundsen Sea sector of the WAIS, which show thinning, retreat and flow acceleration of various outlets of the ice sheet. There is an ongoing debate as to whether these changes represent the onset of WAIS collapse, or are part of hitherto unseen natural variability. But the rapidity of change in this region, coupled with its potential to contribute as much as 1.5 m to global sea-level (Hughes, 1981; Vaughan, 2008) have stimulated efforts to understand and predict the WAIS. An important part of this effort has focussed on the palaeo record of ice sheet change.

2. The Antarctic palaeo record

The record of past change in the Antarctic ice sheets is important for a number of reasons that impinge directly on the debate about contemporary and future change. These are

- ice sheet trajectory
- model testing
- range and types of natural ice sheet variability
- identification of forcing mechanisms for ice sheet change
- ice sheet/sea-level budget for Earth
- correction of contemporary glaciological measurements
- biological dispersal and evolutionary change in polar ecosystems

I outline below how each of these relate to the debate on contemporary and future ice sheet and environmental change. The focus throughout is on what the palaeo record tells us about ice sheet volume, and thus sea-level change. Ice core records, marine, and lake sediment records of Antarctic palaeoclimate have been reviewed elsewhere recently (e.g. Hodgson *et al.*, *in press;* Bentley *et al.*, 2009) so I do not consider them in detail here.

2.1. Ice sheet trajectory

Understanding the history or 'trajectory' of Antarctic Ice Sheets in recent centuries and millennia is important for interpreting contemporary change. Ice sheets have long reaction timescales because of processes such as isostasy, thermomechanical coupling and advection of ice with different rheological properties in the basal shear layers (e.g. Huybrechts and de Wolde, 1999). This means they can respond slowly to climate change and their behaviour over millennial timescales can profoundly affect the interpretation of forcing mechanisms for recent change. Figure 3 shows two hypothetical scenarios of ice sheet change since the Last Glacial Maximum (LGM). In the first scenario the ice sheet responded to warming at the end of the glacial period by starting to thin progressively; a trend that continues to the present day. In this case the thinning over recent decades is simply a continuation of the long-term geological trend. In the second scenario the ice sheet thinned rapidly following the last glacial, reaching a much smaller configuration early in the interglacial. In this case, any thinning trend measured now is more likely to be due to a recent shift in atmospheric or oceanic forcing rather than a slow ice sheet response.

Clearly these are end members of a spectrum of possible behaviour but they illustrate the point that ice sheet trajectory is important for understanding and interpreting forcing of contemporary ice sheet change. Recently-acquired geological data from various parts of the Antarctic Ice Sheets show that both these scenarios are represented in different sectors of the ice sheets. For example, Stone *et al.* (2003) showed that in the Ford Ranges area of the WAIS the ice sheet has thinned progressively for over 10 ka. As noted by Vaughan (2005) the long-term average thinning rate in the Ford Ranges is ~2.5-9 cm/yr, which compares closely to the satellite-altimetry derived figure of ~ 2-8 cm/yr for the period 1992-2003 (Davis *et al.*, 2003). The grounding line retreat in the Ross Sea sector has also been gradual and continuous for most of the Holocene (Conway *et al.*, 1999) with a long-term geological average retreat rate of 120 m/yr, which compares to contemporary measurements of 30 m/yr (Ice Stream C, 1974-1984: Thomas *et al.* 1988) to 450 m/yr (Ice Stream B, last 30 years: Bindschadler and Vornberger, 1998). Evidence of similar progressive thinning through the Holocene of the WAIS in the Weddell Sea embayment has been found in the Ellsworth Mountains (Bentley *et al.*, 2007).

Elsewhere, retreat following the LGM was rapid and stepped. For example, on the west side of the Antarctic Peninsula, Bentley et al (2006) showed that the ice stream occupying George VI Sound and Marguerite Bay (Fig. 1) at the LGM (Ó Cofaigh *et al.*, 2002) retreated and thinned rapidly such that grounded ice had retreated to near the present grounding line by 9.5 ka. In the Framnes Mountains (Fig. 1) the East Antarctic Ice Sheet (EAIS) thinned during the Early Holocene, reaching its present level by ~ 6.5 ka (Mackintosh *et al.*, 2007).

An understanding of trajectory is also important for initialising ice sheet models that seek to predict future change. For example, a model seeking to predict future ice mass change in the Ross Sea sector in response to various climate scenarios will require that its long-term response (Stone *et al.*, 2003; Conway *et al.*, 1999) is incorporated adequately in the physics of the model. In other words, it is not necessarily possible to predict future ice sheet change simply by measuring today’s ice sheet configuration, assuming this is an equilibrium state, and then applying forcing scenarios. Moreover, the past trajectory may have important practical implications for the length of time required for models to be run in their initialisation phase: the more important the long-term behaviour the more likely the model will require to be run over longer timescales.

2.2. Data against which models can be tested

Any model which seeks to predict future change in natural systems needs to be tested against observations in some way. In the case of weather forecasting, the performance of atmosphere-ocean models can be tested by comparing their model output against past, known configurations (Vaughan and Arthern, 2007). Differences between model and measurement can be used to identify problems, or improvements to the model. A similar approach can be taken for ice sheet models where the performance or ‘skill’ can be tested against known past configurations of the ice sheet. The problem here is that, compared to weather models, there is much less information on past configuration of the Antarctic Ice Sheets. Moreover, the data that do exist are fragmentary in nature, both in space and time, and may have significant errors associated with for example, the dating of the evidence. This has made testing models of the Antarctic ice sheet a challenging task (Vaughan and Arthern, 2007).

Past field-based reconstructions of the ice sheet typically involve a synthesis of marine geological data (e.g. grounding line position, flow directions, basal conditions, dates) and terrestrial data (e.g. upper ice sheet surface elevation, flow directions, dates). For these to be most useful the reconstructions are best presented in a form that can be used as a basis against which to test models – usually snapshots or 'time-slices' of past ice sheet configurations. There have been a number of these, ranging from the Climate: Long range Investigation, Mapping, and Prediction (CLIMAP) reconstruction (Denton and Hughes, 1981), through to more recent initiatives such as the Environmental Processes of the ice age: Land, Oceans, Glaciers (EPILOG) project (Clark and Mix, 2002) which included reconstructions of the Antarctic ice sheet (Anderson *et al.*, 2002; Denton and Hughes, 2002). There have also been reconstructions of key sectors of the WAIS such as the Ross Sea (Thomas and Bentley, 1978; Drewry, 1979; Denton et al, 1989; Denton and Hughes, 2000) and Weddell Sea (Bentley and Anderson, 1998; Bentley, 1999; Sugden *et al.*, 2006) embayments. All of these have tended to focus on the LGM configuration of the Antarctic Ice Sheets, because this is the time period for which we know most. Other, deglacial time-slices are less well-known and very few reconstructions exist. A notable exception is the IJ05 series of LGM-to-present reconstructions by Ivins and James (2005). These are derived from field evidence rather than ice sheet modelling, and have linear interpolation between time intervals. The IJ05 reconstructions are specifically aimed at providing an ice loading history for models of Glacial-Isostatic Adjustment (GIA), and thus as a way of correcting contemporary geodetic and gravity measurements for past ice loading (see Section 2.6 below).

It is beyond the scope of this review to go into the detail of each of these reconstructions but it is worth noting that each requires a wide array of field data, including marine geophysics and core sedimentology, terrestrial geomorphology, radiocarbon dating, and cosmogenic isotope surface exposure dating, plus relative sea-level data from raised marine features. The reconstructions require regular updating because of the rapid advances in several of these fields. For example, there is a need to update reconstructions to take account of recent terrestrial data from the Ross Sea and Weddell Sea embayments, and around the East Antarctic margin. All of these findings have modified our understanding of past behaviour of the Antarctic Ice Sheets and could be used to help develop more advanced ice loading histories, to build on the work of Ivins and James (2005).

2.3. Volume of excess ice in the LGM Antarctic Ice Sheets

Ice sheet reconstructions are also important in the debate about the planetary water budget during and since the LGM. The partitioning around the earth's surface of the ~ 120 m of global sea-level rise remains problematic (Andrews, 1992), particularly as a number of ice sheet volume estimates (including Antarctica) have been revised downwards. Bentley (1999) discussed the Antarctic ice volumes derived from reconstructions based on field evidence, glaciological modelling, and GIA modelling, and showed that although historically there have been a wide range of estimates for the amount of excess ice (equivalent sea-level rise, $\Delta\xi$) from 0.5 to 37 m, the more recent estimates have agreed that the value of $\Delta\xi$ is almost certainly < 20 m, and may perhaps be lower than 10 - 15 m (Table 1). This has implications for several fields. It means that the 'missing water' problem (Andrews, 1992), or failure to balance the global water/ice budget at the LGM, remains a challenge. Moreover, it makes it difficult to attribute a sole Antarctic source to meltwater pulse 1A, and that estimates of post-glacial GIA in some studies may have been overestimated, which will necessitate revision of GIA corrections to contemporary geodetic measurements. These latter issues are discussed in more detail later.

2.4. Range and types of natural ice sheet variability

The palaeo record can be used to demonstrate both the range and types of natural ice sheet behaviour. This is important when considering future change as it can yield critical information on 'types' of behaviour that may lead to rapid change. Specific examples I discuss here are the evidence for episodes of rapid retreat leading to ice sheet collapse, whether it is partial (e.g. meltwater pulses) or full collapse (e.g. WAIS absence), and the different styles of Antarctic ice sheet retreat represented in the geological record. I also discuss briefly those areas of the ice sheet that are considered to be relatively stable and so are thought less likely to contribute to sea-level in a warmer world.

2.4.1. Rapid retreat

We know ice sheets can retreat or collapse quickly because we have palaeo evidence of large volumes of ice(bergs) in the ocean (Heinrich Events), but also from indirect evidence such as far-field sea-level records from corals that show very rapid rises in sea-level (meltwater pulses). The most important of these is meltwater pulse 1A (mwp-1A), a period of rapid (~20 m in < 500 years) sea-level rise starting 14.5 ka first identified in the Barbados coral record (Fairbanks, 1989). The source(s) of this meltwater pulse remains rather enigmatic – Fennoscandian, Barents Sea, Laurentide, and Antarctic (Clark *et al.*, 2002; Weaver *et al.*, 2003; Peltier, 2005; Bassett *et al.*, 2007) ice sheet sources have all been discussed but in each case there are difficulties in reconciling the records of ice sheet or meltwater discharge history (e.g. see review in Clark *et al.*, 1996). In the case of Antarctica, the downwards revision of LGM ice sheet volume estimates (Table 1), along with widespread evidence of progressive (rather then stepped) WAIS thinning makes it difficult to find enough ice in Antarctica to make a large contribution to mwp-1A. This remains a key research area in Antarctic palaeo-research and its resolution is required in order to fully understand real, rather than theoretical, rapid changes in ice sheets.

A further challenge for palaeo researchers is finding ways to measure the *rate* of past sea-level rise from Antarctica (and other ice sheets). In some respects understanding the likely rates of future sea-level rise is at least as important to policymakers as its eventual magnitude (Nicholls and Lowe, 2006): an understanding of how this has varied in the past can help.

Whether or not there have been pulses of meltwater from Antarctica, there is an apparent lack of evidence for Heinrich-type events around much of the continent. Ó Cofaigh *et al.* (2001) showed that sediment cores from the Pacific margin of the Antarctic Peninsula and from the Weddell Sea did not have prominent episodes of ice-rafted debris (IRD) that could be attributed to widespread collapse of the ice sheet margin. Some IRD layers were identified but these were due to low sedimentation rates and current winnowing. Away from the margin, Kanfoush et al (2000) found IRD in South Atlantic cores but their interpretation has been questioned (Clark and Pisias, 2000), and the finding has not been replicated. Understanding past iceberg discharge is important as it is one of the primary ways that the Antarctic ice sheet can lose mass.

2.4.2. Past WAIS collapse

A key question in Antarctic glaciology is whether the WAIS has ever collapsed before. This impinges directly on the instability argument because if it has collapsed it demonstrates the real, rather than theoretical potential for collapse, and can be used to identify processes that limit or promote rapid retreat. Moreover, if we can identify a period of past collapse then it holds the prospect of using the palaeoclimate and palaeoceanographic records to identify the necessary forcing conditions for WAIS collapse. In particular, ice cores show that some interglacials were warmer than present (EPICA Community Members, 2004): did the WAIS survive these interglacials ? Because of its potential importance for the debate on future WAIS (in)stability I address the question in some detail here.

The possibility of past WAIS collapse was first discussed by Mercer (1968), who used the evidence of higher-than-present sea-level to suggest it may have occurred during the last interglacial. Scherer (1991) suggested previous WAIS collapse on the basis of marine diatoms he found in till sampled from the base of a drill hole in the upper part of Ice Stream B (now renamed 'Whillans Ice Stream'). He argued that some of the marine diatoms dated from the Pleistocene and therefore implied that the area must have been open to the sea at some point in this period, implying WAIS retreat to at least this point. He refined the dating further, arguing that the absence of a key marine species, *Actinocyclus ingens* that became extinct at 0.6 Ma implies that the sub-Whillans Ice stream assemblage post-dates this. The most likely candidate periods for full or partial WAIS collapse were either or both of Marine Isotope Stage (MIS) 11 (~400 ka) or MIS 5e (~120 ka). The evidence for the timing of WAIS collapse was challenged by Burckle (1993), arguing that extinction of *A. ingens* was earlier than 0.6 Ma, and was a diachronous event (its extinction happened earlier nearer Antarctica), so could not be used to constrain the timing of WAIS collapse. Moreover, he questioned why common marine diatom species - apparently well-suited to the area deglaciated by WAIS collapse - were not found at all in the subglacial sediment.

Scherer (1993) defended his diatom stratigraphy against these arguments, and more recently, Scherer *et al.* (1998) re-sampled till from boreholes beneath Whillans Ice Stream and found similar assemblages but with some Quaternary diatom species not encountered in the earlier study. They also measured ^{10}Be concentrations in the sediment, which they argued derive from the seawater in which marine sediments were originally deposited. In samples containing Quaternary diatoms the measured ^{10}Be concentrations were high (up to 5.4 x 10^8 atoms/g), implying a maximum age of 3 Ma for the sediment. To counter arguments that the ^{10}Be was derived from meltout of ice they measured ^{10}Be concentrations in till samples with no Quaternary diatoms. These yielded 'background' levels ($<10^6$ atoms/g), suggesting that the ice is an insignificant source of ^{10}Be to the sediment (Scherer *et al.*, 1998). This in itself is an interesting result as it implies that the residence time of water in the subglacial sediment is relatively short, a result consistent with subsequent observations of water movement beneath this ice stream (Fricker *et al.*, 2007). The lack of lacustrine diatoms in all samples was used to counter arguments that the diatom assemblage (and adsorbed ^{10}Be) might be windblown on to the surface of the ice (e.g. Kellogg and Kellogg, 1996; Burckle and Potter, 1996). The new diatom and ^{10}Be data have provided a more convincing case for WAIS collapse but this work too has been challenged partly because at least one multi-proxy record of marine sediment from the margin of West Antarctica shows no evidence of a collapse event in the last ~ 2 My (Hillenbrand *et al.*, 2002).

There is also widespread indirect evidence of ice sheet collapse in the form of high marine deposits from the last interglacial in far-field locations, implying a higher-than-present sea-level (see compilation of evidence in Table S1 of Rohling *et al.*, 2008). The evidence ranges from coral terraces in Barbados (Thompson and Goldstein, 2005) to elevated reef deposits in western Australia (Stirling *et al.*, 1995), and suggest that during MIS 5e mean sea-level was 4-6 m higher than present (Rohling *et al.*, 2008). Within the interglacial there were significant fluctuations in sea-level, perhaps by as much as 10 m around the mean (Rohling *et al.*, 2008). However, as yet the source of the higher sea-level has not been conclusively apportioned to Greenland or Antarctica: each ice sheet could have contributed up to 6-7 m (Cuffey and Marshall, 2000).

So where does this leave us in terms of past WAIS collapse? The far-field relative sea-level (RSL) data seem compelling in their implication of more advanced deglaciation (of Greenland and/or Antarctica). Scherer's (1991; 1993; 1998) data show intriguing characteristics that suggest past WAIS collapse *at some point*, but the dating is difficult because of the fragmentary, deformed nature of subglacial sediment (Burckle, 1993), and the apparent lack of evidence from marine sediments around Antarctica (e.g. Hillenbrand *et al.*, 2002). A further difficulty is inferring *full* WAIS collapse from the presence of marine waters at the location of Whillans Ice Stream. Some model simulations of WAIS collapse suggest that this area could be deglaciated fairly early on in WAIS collapse, and that a significant ice sheet would remain in the interior at this time (e.g. Warner and Budd, 1998). However, more recent modelling suggests that deglaciation to this point does imply major WAIS retreat (Pollard and DeConto, 2009). So whilst further investigations of subglacial sediment would undoubtedly be useful, particularly in investigating the spatial extent of a deglaciated WAIS interior, there are strong arguments for looking at stratigraphically-continuous records to try and identify dateable period(s) of collapse. Burckle (1993) argued marine sediment records around Antarctica should be used but these also have their own problems (Scherer, 1993). One alternative approach is to recover sediment records from sub-glacial lakes. If the location(s) are carefully chosen to represent sites deglaciated in the latter stages of WAIS collapse, and if the sediments escaped erosion during initial re-glaciation, then such sediments may hold a record of marine or lacustrine deposition which could be dated directly using palaeomagnetic techniques without reliance on microfossil stratigraphy. This holds the prospect of tying together the far-field RSL data and geological evidence of WAIS collapse to identify well-dated periods of collapse. Only then are we likely to identify the environmental conditions that have led to past WAIS collapse. By inference, periods of high sea-level without evidence of WAIS collapse might be attributed to Greenland.

An alternative approach would be to use sea-level fingerprinting (Mitrovica *et al.*, 2001) of the elevated interglacial deposits in order to identify the source ice sheet(s). This has not yet been attempted for last interglacial deposits, and indeed would be a challenge because of the need for deposits of the same age (requiring precise dating), and each with high precision elevations and clearly understood indicative meaning with respect to sea-level (Shennan 1982).

Finally, what is perhaps more surprising than rapid ice sheet retreat and sea-level rise is the finding that ice sheets may be able to *grow* rather rapidly, possibly even during interglacials. This evidence modifies the view of a slow build-up and rapid collapse of ice sheet volume (the 'saw-tooth' glacial cycle) and comes from last interglacial deposits and MIS 3 deposits showing rapid *falls* in sea-level (e.g. Siddall *et al.*, 2006; Thompson and Goldstein, 2005). This finding has not really been followed up in Antarctica: for example, few models have yet to examine in detail the rate of Antarctic ice sheet growth within an interglacial.

2.4.3. Styles of retreat

A burgeoning body of marine geophysical data (e.g. see Anderson, 1999) has shown that different sectors of the Antarctic ice sheet show different patterns, or 'styles' of retreat: importantly these have different rates of recession. Three main styles have been identified (Ó Cofaigh *et al.*, 2008) (Fig. 4): (1) Rapid retreat by flotation and calving; (2) Episodic retreat between stillstands, and (3) Slow retreat of grounded ice. The presence of differing styles of retreat for palaeo-ice streams, between different bathymetric troughs is a strong indication that ice streams did not respond uniformly to external forcing at the end of the last glaciation (Sugden *et al.*, 2006; Ó Cofaigh *et al.* 2008). Bathymetry and drainage basin size may be important controls on retreat of individual ice streams. The work by Ó Cofaigh *et al.* (2008) also makes the point that past retreat of ice streams on reverse slopes has not necessarily always been catastrophic. One possible explanation for this is the recent work by Anandakrishnan *et al.* (2007) who have imaged a grounding zone wedge beneath the present-day WAIS grounding line. Alley *et al.* (2007) showed that such wedges can stabilise grounding-line positions in a similar manner to morainal banks at the termini of tidewater glaciers: modelling suggests that moderate sea-level rise will not destabilise the grounding-line, but that larger sea-level rise can do so (Alley *et al.*, 2007). Glaciological observations from some of the Ross Sea ice streams show century-scale cycles of stagnation and reactivation, in line with the palaeo record of episodic retreat (Hulbe and Fahnestock, 2007).

As well as information on styles of retreat the palaeo record can be used to determine the processes operating at the bed of the ice sheet (e.g. see Ó Cofaigh *et al.*, 2007; Ó Cofaigh and Stokes, 2008 and references therein), which is a critical (and difficult) part of parameterising ice sheet models (Vaughan and Arthern, 2007). In particular it is critical to understand the role of ice-bed coupling (e.g. MacAyeal, 1992), including the role of basal hydrology beneath ice streams. Ice streams are the main conduits for ice leaving the ice sheet and so even relatively small variations in their basal conditions can cause significant change in ice volume. Recent work has begun to demonstrate the character of subglacial meltwater drainage beneath palaeo-ice streams (e.g. Lowe and Anderson, 2003; Anderson and Oakes-Fretwell, 2008), at a time when we are beginning to understand water movement beneath contemporary ice streams. Whilst important, much of the palaeo record that is being used to understand these subglacial processes comes from outside Antarctica, and has been very recently reviewed elsewhere (Ó Cofaigh and Stokes, 2008) so I do not consider it further here.

2.4.4. Ice shelf collapse

The collapse of Antarctic Peninsula ice shelves in recent years has been identified not only as a significant impact of contemporary warming in the region, but has also caused increased discharge of grounded ice to the ocean (Scambos *et al.*, 2004; Rignot *et al.*, 2004). The palaeo record has been important in this debate because of the identification of former ice shelf collapse during the Holocene, and its spatial pattern. Following the collapse of Prince Gustav, Larsen-A, and Larsen-B ice shelves, sediment cores were retrieved from those parts of the continental shelf previously covered by floating ice on the east side of the Peninsula. These suggested that Prince Gustav Ice Shelf had collapsed before, probably in the mid-Holocene (Pudsey and Evans, 2001) but that the 2001-02 collapse of Larsen-B was the only time it had collapsed in this interglacial (Domack *et al.*, 2005). On the west side of the Peninsula, Bentley *et al.* (2005) showed that the George VI Ice Shelf retreated significantly in the Early Holocene (9600-7900 yr BP). The Prince Gustav Ice Shelf retreat was linked to a well-documented mid-Holocene warm period (Pudsey and Evans, 2001) whilst the retreat of George VI Ice Shelf immediately followed a period of peak atmospheric warmth recorded in ice cores, and was probably associated with an influx of warm ocean waters onto the continental shelf (Smith *et al.*, 2007).

The palaeo record has therefore been able to demonstrate that contemporary ice shelf behaviour is not without precedent, and that it is possible to link past ice shelf behaviour to proxy records of atmospheric or oceanic warming. Hodgson *et al.* (2006) reviewed the spatial pattern of Holocene ice shelf behaviour and showed that since Holocene retreat occurred south of the contemporary limit of ice shelf stability then there may have been different oceanic or atmospheric forcing configuration at these times. Additionally, Domack *et al*'s (2005) suggestion that the Early Holocene Larsen-B ice shelf was especially thick, and therefore more resistant to sustained warming, might have been important.

2.4.5. Stability of the East Antarctic Ice Sheet

The EAIS is dominantly a terrestrial ice sheet (bed above sea-level) with only relatively minor areas grounded below sea-level. A long-running debate contested whether the ice sheet retreated significantly during a previous (Pliocene) global warm period, or whether it remained largely stable. Summaries of the main arguments can be found in Sugden *et al.* (1993) and Wilson (1995). As with the debate on WAIS collapse, much of the argument centred on the presence of marine diatoms in glacial sediments. In this case the sediments were high elevation tills in the Transantarctic Mountains. A likely aeolian origin of the diatoms has been demonstrated for several of the key localities (e.g. Stroeven and Prentice, 1997), reducing the requirement of a deglaciated EAIS interior from which to source such diatoms. The balance of evidence now seems to be in favour of a relatively stable EAIS with geomorphological evidence of intense aridity and cold climate, at least in the Transantarctic Mountains, for several millions of years.

However, some recent measurements of thinning at the termini of the Cook and Totten Glaciers (Davis *et al.*, 2003; Wingham *et al.*, 2006) - which occupy large basins below sea-level - have once again prompted the question of whether past or future retreat of these areas might occur, or might have occurred. If so it implies that significant areas of the EAIS (amounting to some metres of sea-level) may have deglaciated in the past. This is not necessarily incompatible with the evidence of stability in the Transantarctic Mountains, as shown in a recent glaciological modelling study by Hill *et al.* (2007). Any such partial deglaciation is testable using palaeo-records from around and beneath the EAIS, and is a clear future research priority. Moreover, this question may also be relevant to the debate on attributing ice sheet sources to high interglacial sea-levels.

2.5. Identification of forcing mechanisms for ice sheet change

One of the pressing questions facing the ice sheet community is identifying the dominant forcing mechanism(s) for change. The palaeo record can help with this as we have the opportunity to examine past spatial patterns of change, and compare to records of sea-level, atmospheric or oceanic change. This is important because it helps identify the critical processes that may require detailed modelling in order to better predict future change (Sugden *et al.*, 2006). For example, Conway *et al.* (1999) showed that the pattern of progressive grounding line retreat in the Ross Sea was not consistent with a simple sea-level forcing mechanism for WAIS retreat. Specifically, the retreat started some time after the northern hemisphere-forced sea-level rise began, and it has continued for several thousand years following the deceleration of postglacial sea-level rise. In contrast, Mackintosh *et al.* (2007) pointed out that the close coincidence between the cessation of ice sheet thinning in the Framnes Mountains (EAIS) and the cessation of major sea-level rise from the Northern Hemisphere may point to sea-level as an important control on EAIS extent.

Heroy and Anderson (2007) reviewed the sediment cores and marine radiocarbon dates that constrain the deglaciation of the Antarctic Peninsula ice sheet (APIS). They took the best dates (i.e. from carbonate organisms, rather than acid-insoluble organic material, and from as close as possible to the onset of deglacial sediment deposition) and used these to suggest that the deglaciation of the APIS occurred between 18,000 and 9000 cal yr BP. They found a reasonably consistent pattern of ice retreat from the outer and mid-shelf but that once on the inner shelf the ice sheet showed locally variable behaviour, possibly related to local topographic controls. Interestingly they suggested that the onset of retreat was earlier in the northern APIS, with retreat starting a few thousand years later in the south. They argued that the timing of initial retreat supported the hypothesis of destabilisation by northern hemisphere-driven sea-level rise, but this does not necessarily explain the north-south contrast. Indeed, it could be argued that the contrast could point to a gradual southwards shift in warmer oceanic or atmospheric temperatures. Modelling of APIS retreat can potentially answer this question.

2.6. Correction of contemporary measurements

Ice sheet mass balance can now be measured by space-borne gravity measurements, such as the Gravity Recovery and Climate Experiment (GRACE). To convert the year-on-year change in gravitational field to an ice mass budget requires a number of corrections, the most important of which is the correction for GIA (sometimes termed post-glacial rebound (PGR)). For example, if successive passes of the GRACE satellite pair detect an *increase* in gravitational attraction over a rebounding area of Antarctica then they require a knowledge of how much of that increase can be attributed to an inwards flow of mantle material (as the crust rebounds), and how much to extra ice. There have been two approaches to this correction. The first of these has been to use the IJ05 model of ice loading and to use this to calculate a GIA-derived mass trend that is subtracted from the 'raw' GRACE-measured mass trend to yield the ice mass change (Fig. 5) (Velicogna and Wahr, 2006; Ramillien *et al.*, 2006; Chen *et al.*, 2006; 2008). These studies have used different generations of GRACE data, and for different time periods and so are difficult to compare directly, but they yield results suggesting ranging from Antarctic ice sheet balance (Chen *et al.* 2006) to a sea-level contribution of +0.38 mm/yr (Velicogna and Wahr, 2006). The second approach to the GIA correction was by Sasgen *et al.* (2007) who used their own visco-elastic earth model forced by four timeslices from the ice sheet model results of Huybrechts (2002) to derive a GIA signal. They then used the resultant GIA signal in the Weddell Sea – the largest part of the GIA signal – to adjust or 'tune' the Huybrechts glacial history to yield a pattern consistent with their GRACE observations. This approach yielded regional estimates of ice mass change for various parts of Antarctica that were reasonably consistent with other GRACE estimates and laser altimetry estimates.

Whilst the approaches and results differ, all of these studies agree on the critical role of the GIA correction (Fig. 5): indeed Chen *et al.*, (2006) suggested that GRACE mass balance measurements might be subject to uncertainties on the order of 100% due to incompletely-known GIA corrections, and that these, '*…constrain the ability of GRACE to provide confident estimates of snow/ice mass loss at present*'. Thus, there is an urgent need to update the ice sheet reconstructions (Section 2.2.), and in particular the time-slice approach of Ivins and James (2005) in order to translate the burgeoning field measurements of ice sheet configuration through deglaciation into useable ice loading histories. The contemporary GIA signal is particularly sensitive to Late Holocene ice loading which is, as yet, poorly known.

2.7. Biological dispersal and evolutionary change in polar ecosystems

Polar ecosystems are already responding to climate change (Walther *et al.*, 2002). Greater impacts are predicted as atmospheric and ocean temperatures rise, possibly including the passing of temperature thresholds for key functions of marine organisms (Peck *et al.*, 2004), potentially leading to a loss of diversity in the Antarctic ecosystem. Conversely, rising temperatures may lead to the invasion of new, non-indigenous species from warmer climatic regimes further north (Frenot *et al.*, 2005). The palaeo record can provide some input to this debate by identifying how polar ecosystems have responded to past ice sheet change. One example of this type of study is the work on organisms preserved in lake or fjord sediments from the fringes of Antarctica. Hodgson *et al.* (2003) used proxy records from the East Antarctic margin to demonstrate significant impacts on marine floras during the last glacial cycle: ice sheet advance removed flora from the inner shelf through denial of light, destabilisation of the substratum and elimination of habitat, whilst species diversity increased post-LGM as species re-colonised the deglaciated areas.

The palaeo record can also be enhanced by knowledge of biological changes. For example, the development of 'molecular clocks' - that use differences in DNA and estimated mutation rates to measure the timing of divergence of DNA lineages - allows the identification of environmentally-driven bifurcations in populations. One such study by Strugnell *et al.* (2008) has shown that Antarctic deep sea octopuses originated c. 33 Ma and that the deep sea lineage showed a marked diversification c. 15 Ma. Interestingly these dates correspond to the initiation of the Antarctic ice sheet and the inferred Miocene expansion of the Antarctic Ice Sheet, and so the octopus divergence dates provides an independent check of the geological dates.

At millennial and much longer timescales, there is biological evidence that certain species such as nematode worms must have been present in refugia on the west side of the Antarctic Peninsula at the LGM and through previous glacial advances (Convey and Stevens, 2007; Convey *et al.*, 2008). The environmental tolerance of many of the species involved imply that at least some of these refugia were close to the coast and at low altitude. Biological evidence from certain mites and springtails demonstrates that ice-free nunataks must have been present in some parts of Antarctica for several millions of years (Convey *et al.*, 2008), but that these cannot have supported the coastal species. Identifying candidate locations for the LGM and earlier refugia is a challenge for geologists and ice sheet modellers, since most field data and ice sheet models suggest that low elevation coastal areas were over-ridden by the expanded LGM ice sheet. One possible resolution to this paradox is that species might have survived on transient supraglacial 'rock' features such as medial and lateral moraines, transported on the surface of the ice from further inland, where exposure dates show nunataks remained exposed during glacial periods. Such supraglacial moraines can provide a suitable substrate for some of these organisms and may have been widespread at the LGM. Alternatively, thin, low profile ice sheets (e.g. Larter and Vanneste, 1995) may have created refugia in upland coastal areas but resolving such high relief areas adequately in models is notoriously difficult. The interface between glacial geology, glaciology and biology is an emerging field, which can potentially provide further constraints on ice sheet models.

3. Conclusions

In this paper I have tried to demonstrate that the Antarctic palaeo record can inform the contemporary debate on climate and sea-level change in a number of important ways. For each of these I have explained the importance and outlined progress to date. The main areas include model testing, providing information on ice sheet trajectory, the range and types of natural variability, identification of forcing mechanisms, correction of contemporary observations, and interactions with polar ecosystems. Active research continues in each of these areas and all are important, but it is perhaps worth concluding here with a personal view on five research priorities for the next few years.

(i) **WAIS collapse.** The identification of spatial patterns of WAIS collapse and robust dating, via ice sheet drilling, including perhaps into subglacial lakes, holds the prospect of a clearer idea of the timing of collapse and necessary forcing conditions for this critical event.

(ii) **Rapid retreat events**. Changes in the Amundsen Sea area have shown that we need to focus on, and understand better, the geological record of past rapid retreat to better inform predictions of future change in this sector.

(iii) **Post-LGM ice sheet reconstructions**. Model testing and correction of contemporary glaciological measurements require better (and more) reconstructions of the ice sheet than we are currently able to provide. In particular we need to improve understanding of ice sheet configuration through the Holocene.

(iv) **Sub-glacial processes**. Amongst the most important – but least well understood - parts of ice sheet model parameterisation are the bed conditions. There is an important interface between glaciology and glacial geology where each can inform the other and an obvious aim is to better infer past ice sheet characteristics from sediments and landforms.

(v) **EAIS dynamics**. The subtleties of the EAIS response to past climate change are still not well known outside the Transantarctic Mountains but given some large basins below sea-level this is an area that deserves closer attention from the palaeo community than hitherto.

Finally, it is clear that this is an interdisciplinary problem. There is a clear need for even more collaboration between glaciologists, geophysicists, modellers, marine geologists, geomorphologists and biologists in order to fully understand the processes governing the Antarctic ice sheets, and thus to stand the best possible chance of predicting their future.

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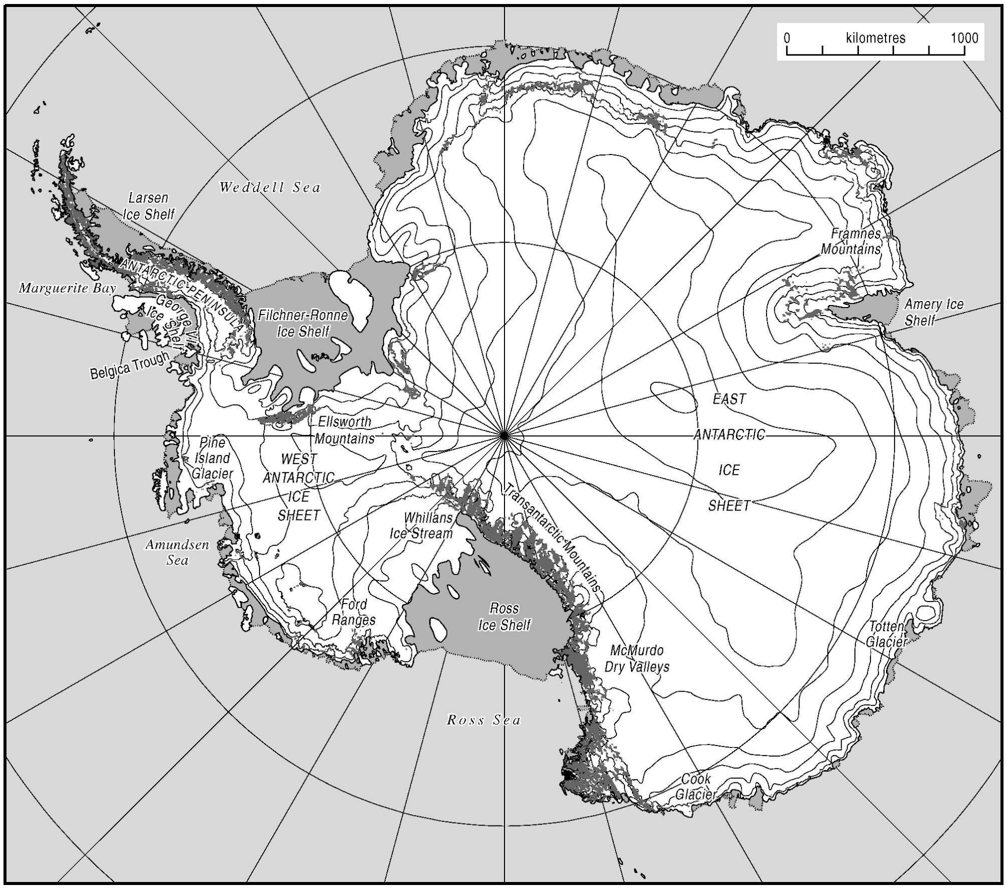
Figure 4. Styles of Antarctic palaeo-ice stream retreat. (a) Rapid retreat (e.g. Marguerite Bay, Antarctic Peninsula). Sub-glacial landforms such as mega-scale glacial lineations (MSGL) are preserved intact with no deglacial landforms and very thin deglacial sediment. (b) Episodic retreat (e.g. Larsen-A shelf and Belgica Trough). Well-preserved MSGL are superimposed by a relatively thin deglacial sediment cover and grounding-zone wedges, marking stillstand positions; (c) Slow retreat (e.g. western Ross Sea). MSGL are superimposed by thick deglacial sediment along with numerous, closely-spaced recessional moraines and occasional grounding-zone wedges. (Reproduced from Ó Cofaigh *et al.*, 2008).

Figure 5. The importance of ice loading history for interpreting GRACE data. IJ05 ice load reconstructions for (a) 21 kyr BP and (b) 7.6 kyr BP. (c) GRACE data for 2003-2006 (expressed as mass rates), and (d) the GIA correction imposed by the IJ05 model (expressed in terms of mass rates). The magnitude of the GIA correction is comparable to the 'raw' GRACE data and so is a critical part of using GRACE data to interpret ice mass change in Antarctica. [Sources: (a) and (b) from Ivins and James (2005), whilst (c) and (d) are taken from Chen *et al.* (2008)]



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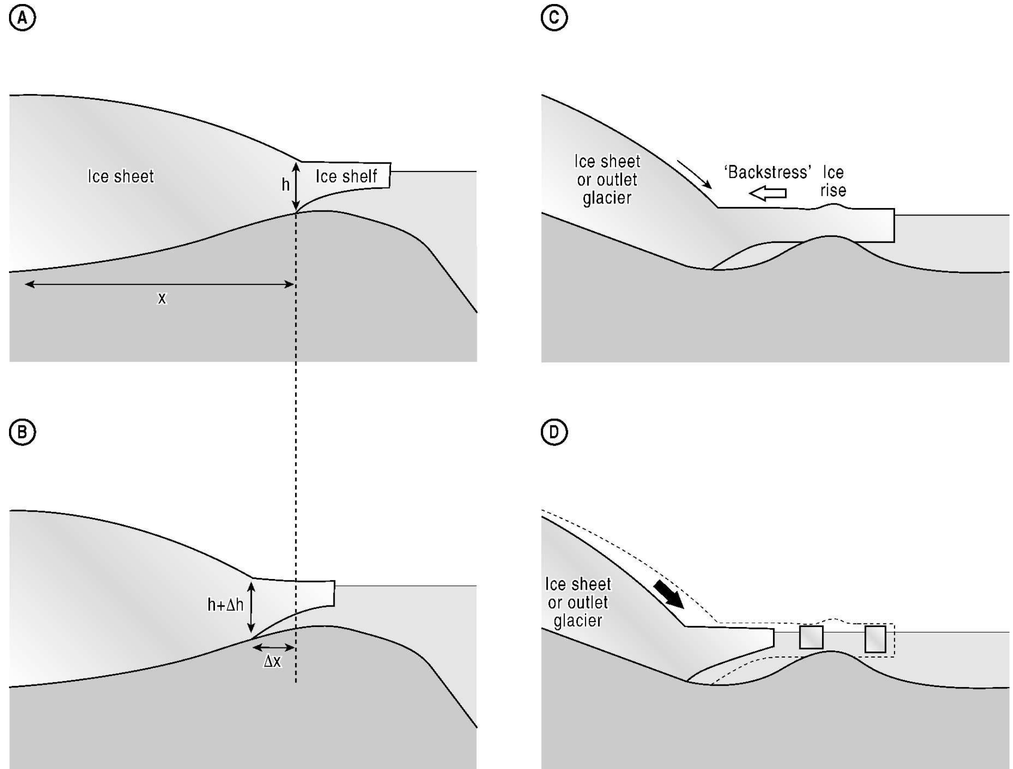

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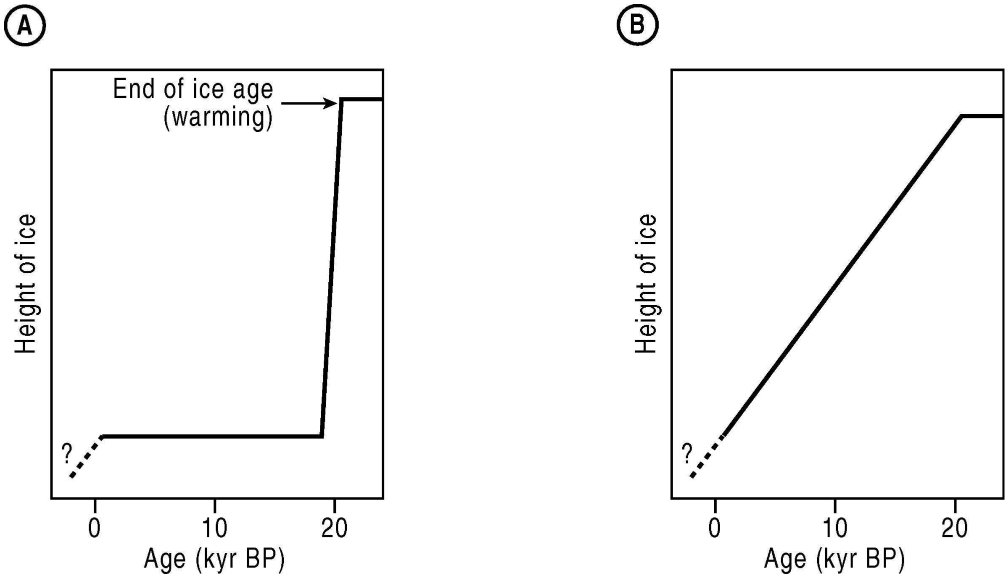

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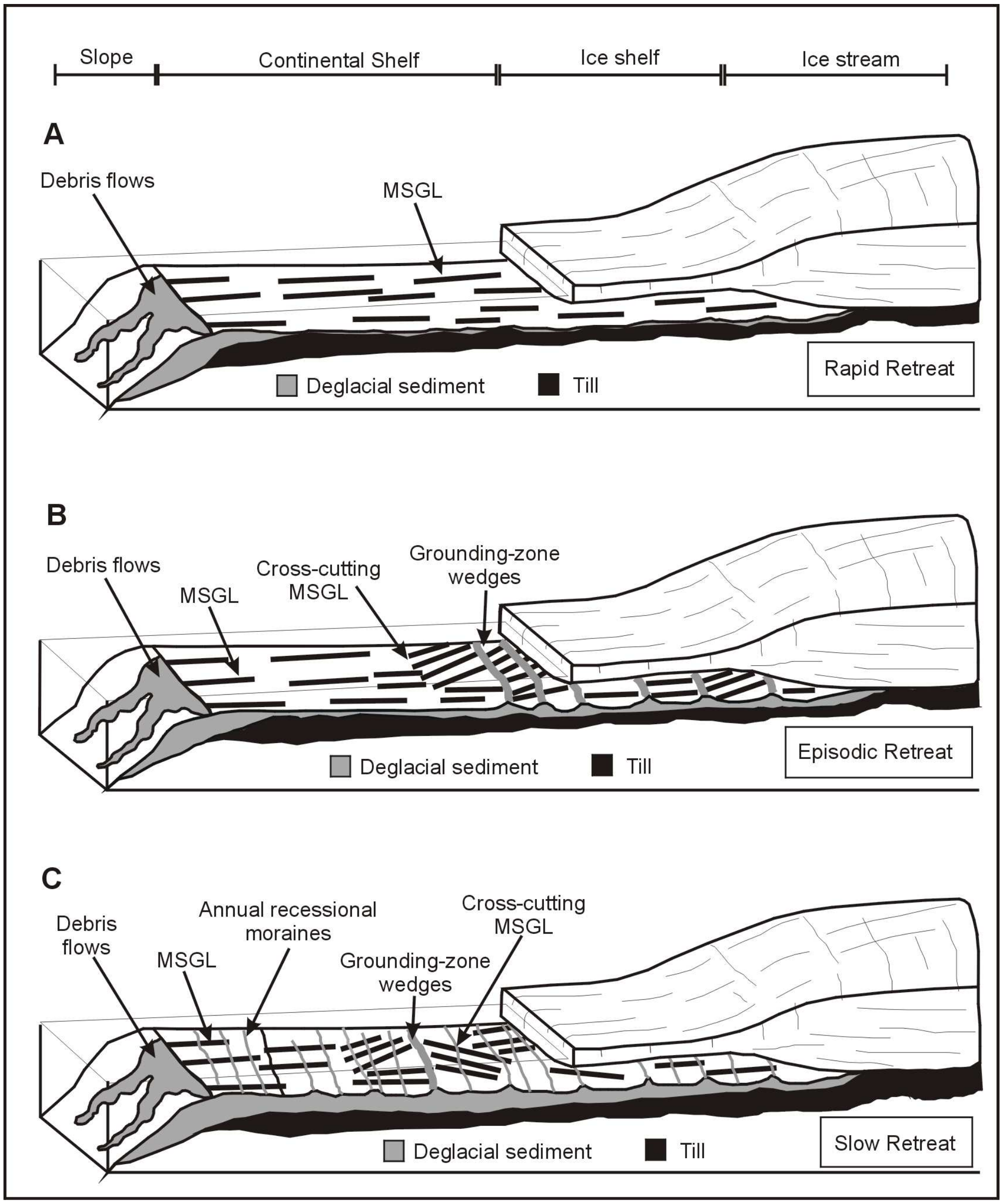

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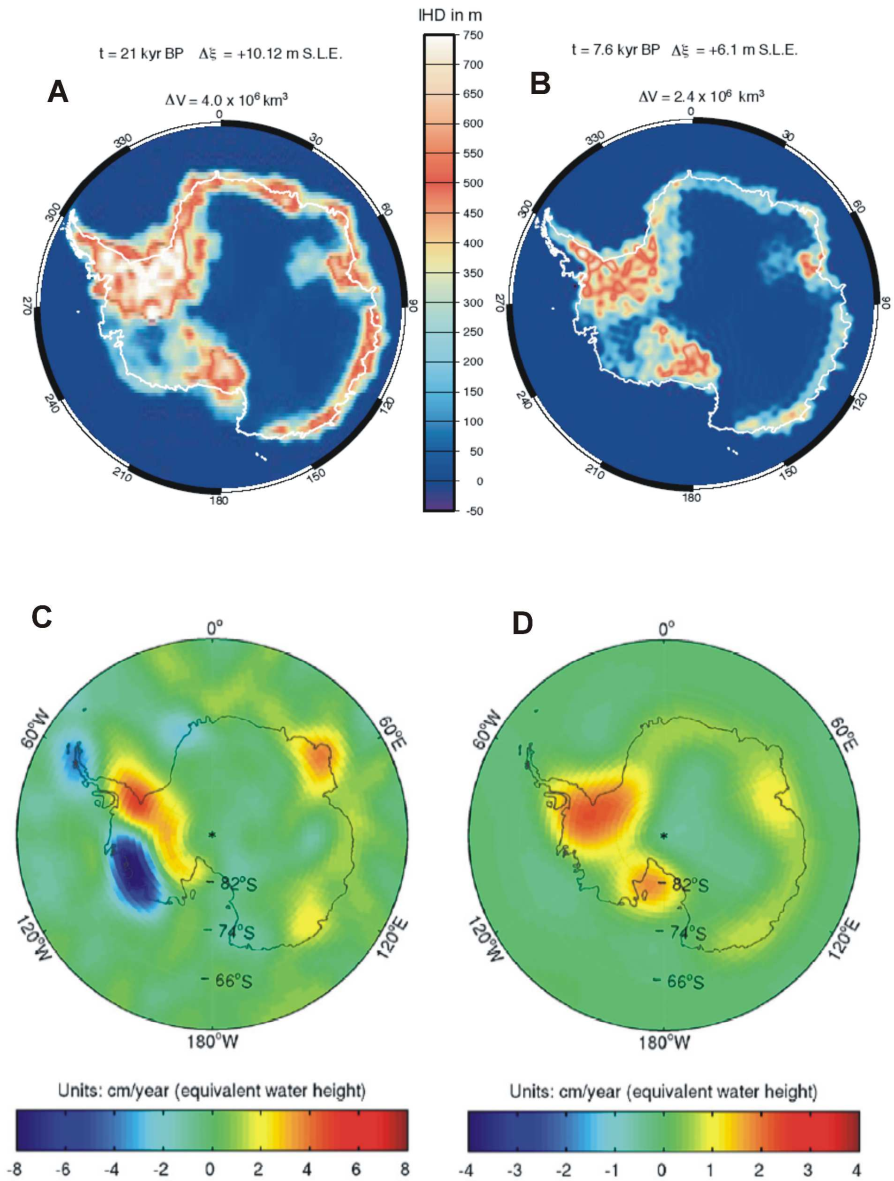

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