THE NOTHAFAGUS PARADOX: A REVIEW OF THE HYPOTHESES FOR ANTARCTIC ICE SHEET BEHAVIOUR DURING CLIMATIC WARMING OF THE PLIOCENE

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1. Introduction

A significant focus of contemporary scientific investigation has been the issue of possible global warming. The notion that the earth's climate is heating up has crucial implications for the future. Thus understanding and further quantifying the possible existence of global warming is extremely important to future populations.

With 30,000,000 km$^3$ of ice comprising the Antarctic cryosphere (Radoc, 1985), of considerable concern is how this resource will react to possible global warming. If all of this Antarctic ice was to melt, the potential for sea level rise has been calculated to be as much as seventy metres (Radoc, 1985). With human occupancy abundantly associated with coastal and flood plain regions of the earth, such sea level rise would no doubt prove catastrophic. Therefore, understanding the history of the Antarctic ocean-cryosphere system - in-particular, its history of response to climate change - is important in assessing future response of the Antarctic region to global warming.

This paper is a review of the literature associated with two hypothesis of Antarctic ice sheet behaviour derived as from analysis of warmer climates of the Pliocene. The two hypotheses that exist are very different to each other and known as the stability hypothesis and the instability hypothesis respectively. By way of introduction, the stability hypothesis is based on the idea that the Antarctic ocean-cryosphere system remained relatively stable during this period of warmer climate. Opposite to this is the instability hypothesis, which is based on the belief that much of the Antarctic ice sheet melted during the Pliocene period of warmer climate.

The paper has its foundations firmly located in the scientific process. Science, in its basic form, involves the creation of a hypothesis, and the search for evidence to prove or disprove such hypothesis. Significant in the scientific process is the interpretation and evaluation of the evidence uncovered. In some instances, the evaluation of the evidence indicate a paradoxical situation, where what some evidence suggests is at odds with the
inferences gained from other sources of evidence. This paper seeks to review the evidence proposed in favour of two paradoxical hypotheses.

The paper will be categorised by five key sections. Firstly, a background section will introduce important ideas that are an integral component of understanding the two hypotheses. Following two sections will be devoted to each of the hypotheses, looking to provide a more detailed account of the hypotheses. Following will be a discussion in two sections, looking to outline the key evidence in support of their distinctive positions, leading into a conclusion, summarising the position of the debate, and indicating the hypothesis for which greater support to exist.

2. Background

The Antarctic cryosphere represents the largest accumulation of ice on Earth, accounting for 90% of the earth's total freshwater source (Radoc, 1985). The Antarctic cyrosphere is characterised by two ice sheets (Figure 1, page 3). The largest of the two ice sheets is the continent based East Antarctic ice sheet, which has a volume of over 26,000,000 km$^3$ that is principally grounded on bedrock above sea level. In contrast, the much smaller West Antarctic ice sheet (over 3,000,000 km$^3$) is grounded below sea level. This difference makes the West Antarctic ice sheet less stable, as it more vulnerable to small changes in sea level and ocean temperature.

These ice sheets and the adjacent Southern Ocean act together to form the Antarctic ocean-cryosphere system. This system represents one of the most important components of the earth's climate system, by strongly influencing global atmospheric and oceanic circulation systems (Cattle, 1991). The Southern Ocean is an integral component of the Antarctic environmental system as the cold circumpolar current maintains the thermal isolation of the continent.

The ocean is bounded to the north by the Antarctic convergence (Figure 1, page 3). This is where cold, nutrient rich Antarctic surface waters to the south are separated from the
warmer, less nutrient rich sub-Antarctic surface water. Up welling of deep water in this region links the mean chemical composition of ocean deep water with the atmosphere through gas exchange (Toggweiler and Sarmiento, 1985).

Figure 1. Outline map of the Antarctic continent, with arrows referring to phenomenon of key interest.

As indicated, the two hypotheses of ice sheet behaviour during warmer climates are based on evidence derived from the Pliocene age. The Pliocene is a historical division of time relating to a period 4.8 to 3.2 million years ago. During this time, climate was warmer than any other time within the past seven million years (Kennett and Vella, 1975; Elmstrom and Kennett, 1986). Analysis of the data from this period should provide information as to how ice sheets responded to this time of what could be classified as global warming.
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Until recently, most involved in the work surrounding the history of ice sheet behaviour focussed on the idea of stability. However, Dave Harwood, Robert Hill and Peter Webb scientifically confronted this idea in 1991 with their discovery of fossilised Nothafagus leaves in the Sirius Group of the Dominion Range, in the Trans-Antarctic Mountains (Figure 1, page 3). Nothafagus is the scientific name given to the Southern Beech tree, and further analysis of the find categorised the fossils as a new species to be known as Nothafagus beardmorensis Hill, Harwood and Webb.

The importance of this find was that it indicated a much warmer climate in the region, a climate that could cause the retreat or even removal of the East Antarctic ice sheet. The characteristics of the species inferred that temperatures in the region had been much warmer than present, whilst the location so close to the South Pole (Figure 1, page 3) lead Hill, Harwood and Webb to propose the hypothesis of ‘instability’.

Stability

The basis of the ‘stability’ hypothesis is that the East Antarctic ice sheet had grown to it’s present size by 14 million years ago. Since this time, it had remained relatively stable under polar desert conditions due to thermal isolation enforced by the circumpolar current (Shackleton and Kennett, 1975; Kennett, 1977; Clapperton and Sugden, 1990; Kennett and Hodell, 1993).

What the hypothesis implies is that the Antarctic ocean-cyosphere system is robust, and that the ice sheets are almost impossible to remove due to the powerful thermal inertia of the circumpolar current. Once plate movement opened the Drake Passage and the Tasmanian seaway (Figure 1, page 3) enabled circumpolar flow, the Antarctic continent became thermally decoupled from the lower southern latitudes (Kennett and Hodell, 1993).

This circumpolar current was well established by 20 million years ago (Lawver et al, 1992), and faunal and sedimentological data indicates a relatively stable position of the
circumpolar current in relation to the breadth of the Southern Ocean (Lazarus and Caulet, 1993). The effect of this relative stability in position of the polar current has been long-term thermal insulation of the continent and resulting stability in the cryosphere.

**Instability**

The instability hypothesis is based on the notion that warming during the Pliocene caused the Antarctic ice sheets to be much smaller and of lower profile than today. The hypothesis invokes a large reduction in the volume of ice comprising the East Antarctic ice sheet (66% of present size), removal of the smaller West Antarctic ice sheet, and considerable warming of Antarctic surface waters (>5°C).

This hypothesis finds its roots in the 1991 geological find in the Sirius group, near Beardmore Glacier in the Dominion Range of the Trans-Antarctic Mountains (Figure 1, page 3). The Sirius group consists of lodgement tills inter-bedded with glacio-fluvial, glaciolacustrine and colluvial sediments. It is within these sediments that the evidence for instability has been found.

Major de-glaciation of the Antarctic ice sheets is inferred from the presence of reworked diatoms and fossilised Beech (*Nothofagus beardmorensis* Hill, *Harwood and Webb*) leaves in the sedimentary deposits. Dating indicated that the deposits were as young as 3.1 to 2.5 million years of age, placing them in the Pliocene. However, for the species to exist, major de-glaciation and warming will have had to have occurred in the past.

The instability hypothesis implies that the Antarctic ice sheets are unstable and susceptible to decay during times warm climatic conditions, such as those experienced in the Pliocene. By analogy, it has also been suggested that the ice sheets may become unstable at elevated carbon dioxide and temperatures, predicted to exist, due to global warming, by 2001 (Barrett, 1991).
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Discussion: The Evidence for Stability

The search for evidence in support of the stability hypothesis has been primarily focussed on the examination of the sedimentary record. Should major de-glaciation have occurred in the Pliocene, clear evidence should exist in marine sediments. The scientific examination of the geologic record contained in the marine record has highlighted six important pieces of evidence in support of the stability hypothesis.

A useful tool in estimating past changes in temperature and global ice volume is the measurement of stable oxygen isotopes in foraminiferal tests. The basic principle is that the $\delta^{18}O$ of calcite is dependent on both the temperature and the isotopic composition of seawater - controlled largely by ice volume - (Kennett and Baron, 1992). Separating out the two signatures from Pliocene sediments enables for the estimation of temperature and the amount of ice present.

The continued evaluation of the relationship between ice volume, temperature and stable oxygen isotope levels ($\delta^{18}O$) has refined the relationship to a level of significant accuracy. The results of analysis of stable oxygen isotopes in foraminiferal tests can be interpreted to represent either a maximum 60 % reduction in ice volume, or a maximum 2.5$^\circ$ Celsius warming of Subantarctic surface waters (Hodell and Venz, 1992). However, it is very unlikely that major de-glaciation could occur without significant warming.

The instability hypothesis predicts an increase in temperature of the Subantarctic surface water of 5$^\circ$ Celsius a two thirds reduction in the volume of the Antarctic ice sheets (Webb and Harwood, 1991). However, the minimal difference in $\delta^{18}O$ levels between the Pliocene and present does not allow for both of these to have occurred. The results only permit ice sheet reduction in the absence of warming (Shackleton et al, 1994).

As noted previously, the instability hypothesis is based on the notion of a two thirds reduction in ice sheet volume (Webb and Harwood, 1991). Such melting would require a major marine transgression associated with a 55 metre increase in sea level (Webb and
Harwood, 1991). Stratigraphic studies at Enewetak Atoll and the U.S. middle Atlantic coastal plain have noted sea levels of 25 to 35 metres higher in the Pliocene than today (Krantz, 1991). However, these figures do not agree with the predicted sea level rise associated with the instability hypothesis.

One mechanism of volume loss from an ice sheet is through iceberg calving. Associated with iceberg calving is ice-rafted detritus. This term refers to the idea that icebergs travel north following calving, and melt in the warmer waters. As the iceberg melts, ice-rafted detritus is deposited onto the seafloor to be incorporated into the sedimentary record. Ice-rafted detritus is found further north during times of cooler ocean temperatures, as this slows the melting process of the iceberg. Associating this to the instability hypothesis, one would expect to see a reduction in the amount of ice-rafted detritus in the sedimentary record, and a contraction southwards in its distribution.

The stratigraphic distribution of ice-rafted detritus was presented quantitatively in 1992 (Warnke et al). It concluded that the Pliocene was characterised by the persistent delivery of ice-rafted detritus in many parts of the Southern Ocean. Also, there was no suggestion of significant reduction in the northward distribution of iceberg sediment transport. This record is consistent with the continued existence of major continental ice sheets on Antarctica during the Pliocene.

Upwelling of deep water at the Antarctic convergence results in high diatom productivity, and the formation of a biosiliceous ooze. This ooze is recorded in the sedimentary record, and relative northward or southward migration of this zone of ooze reflects movement in the Antarctic convergence. For the instability hypothesis to work, warming would result in the southward migration of this boundary in the Pliocene sedimentary record. Similarly, the changing temperature of the surface water associated with the hypothesis would result in a population boom of nanoplanckton, which one would also expect to be contained in the geological record.
Core analysis from drilling projects has indicated that during the Pliocene the zone of biosiliceous ooze remained relative stable. Similarly, the results indicate the general absence of nanoplanckton in the record. The sedimentologic data provide no compelling evidence to support a major southward migration of the Antarctic convergence associated with warming related to the instability hypothesis. Associated is the absence of nanoplanckton in the record, inferring that surface water temperatures remained cold, and that a broad zone of cold Antarctic waters continued to insulate the continent (Burckle and Pokras, 1991).

The Southern Ocean biota is among the most distinctive on Earth, containing a very high level of endemism in many taxonomic groups. This endemism reflects the relative isolation of fauna since the formation of the Antarctic convergence (Clark and Crame, 1989). Strong endemism requires quite stable conditions over a long time period. Had warmer waters displaced the colder Antarctic waters during the Pliocene, much of this endemism would have been lost.

Similarly, many of the species display specialisation to the extreme environment in which they exist. This strongly suggests long-term environmental stability. Pliocene warming must have therefore been of insufficient magnitude to reverse the developing endemism of Antarctic biota (Clare and Crame, 1989).

Dating used in the hypothesis for instability relates to diatoms founding the sedimentary record, and the concept that they were transported there by the renewed glaciation following the warming of the Pliocene. Those in favour of the stability argue this, and believe that atmospheric (largely eolian) processes introduced the diatoms. Testing this eolian hypothesis is relatively simple, based on the idea that if diatoms were introduced by eolian processes to the Sirius group, then they should also exist in older (Paleozoic and Mesozoic) rocks (Burckle and Potter, 1996).

Analysis of samples from the Beacon Supergroup and Marie Byrd Land found Pliocene – Pleistocene planktonic marine diatoms in all sample sets. Because these rocks are older
than Pliocene – Pleistocene in age, it can be inferred that these diatoms were introduced by eolian processes (Burckle and Potter, 1996). This result makes it entirely plausible that the diatoms used for dating renewed glaciation in the Sirius group could be the end result of another process.

Finally, had there been a 66% decrease in the volume of the Antarctic ice sheets associated with instability, it is likely that vegetation would have been present on the continent, especially in coastal areas. It is expected that this vegetation would have supplied pollen and spores to nearby marine sediments. This is even more likely considering the vegetation of Pliocene age discovered in the Sirius outcrop.

No evidence of terrestrial vegetation has been uncovered in numerous sites drilled close to the environment. The youngest pollen assemblages reported from Antarctica that unequivocally reflect terrestrial vegetation are Oligocene in age (Middenhall, 1989). The absence of Pliocene pollen and spore evidence in support of vegetation is an indication that much of the terrestrial environment of Antarctica remained covered in ice during the Pliocene.

**Discussion: The Evidence for Instability**

The key evidence in support of the hypothesis for instability is the presence of *Nothafagus beardmorensis* Hill, Harwood and Webb in high altitudes (2000 to 2500 metres above sea level) of the Sirius group. The presence of this fossil provides the evidence of warmer climate and ice sheet retreat, as this is the only scenario in which one could expect the Southern Beech tree to exist on the Antarctic continent. This is not the major evidence for instability, as that fossil could be associated with the historical setting of Antarctica as a part of Gondwana Land. The date that has been assigned to the fossil is the evidence that infers instability.

Dating the find was based on the presence of reworked oceanic diatoms in the sedimentary unit in which the *Nothafagus* was found. Dating inferred that these diatoms
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were quite young, even as young as the late Pliocene age (3.1 to 2.5 million years ago). Instability infers that these diatoms lived in marine basins within the Antarctic craton. Following the warming of the Pliocene, it is believed that the diatoms, together with basinal sediment, were transported up to the Trans-Antarctic Mountains by developing ice sheets some 2.5 million years ago, the age of the youngest diatoms in the sedimentary structures of the Sirius group (Webb and Harwood, 1991; Hill and Truswell, 1993).

Following the discoveries and inferences made in relation to the Sirius outcrop, more evidence was collected in support of instability. Within the Vestfold Hills region of Antarctica, vertebrate fauna and bivalves have been found in sedimentary structures. This deposit infers the existence of a much higher sea level than today, whilst analysis of oxygen isotope levels ($\delta^{18}O$) infer that seawater temperature was higher, and that global ice volume was far less than that of today (Quilty, 1993). Accurate dating of these deposits has not been possible, though a Pliocene age is quite plausible.

The idea that if there had been a major reduction in the volume of ice during the Pliocene, that a sea level rise would have occurred was also embraced by those searching for evidence in support of the instability hypothesis. Evidence was found for high stands of sea level during from stratigraphic studies at Enewetak Atoll and the U.S. middle Atlantic coastal plain. The results of these studies infer possible maximum high stands of sea level during the Pliocene of 25 to 35 metres higher in than today (Haq et al., 1988; Dowsett and Cronin, 1990). These results are short of the 55 metres of sea level rise inferred by the instability hypothesis, but have associated with them a $\pm$ error of 18 metres, lifting them up to this level.

Finally, marine sediment assemblages of planktonic microfossils have been discovered within the waters between the convergence zone and the continent. (Abelmann et al., 1990; Ishman and Reick, 1992). These fossils have been dated, and results indicate that these organisms were deposited during the Pliocene. For these organisms to have existed, surface waters would have needed to be much warmer than they are today. Their
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Proximity to the continent, and age indicate warmer Antarctic surface water during the Pliocene.

Conclusion

The aim of this review paper has been to identify the range of evidence in support of two differing hypothesis of ice sheet behaviour during periods of warmer climate. What has been presented is a comprehensive overview of the key areas where evidence has been collected with reference to the two differing scientific opinions.

The hypothesis of instability is one that finds its foundations in the geologic find of Nothofagus beaumontensis Hill, Harwood and Webb. The analysis of this find in 1991 led to the findings that form the key components of the instability hypothesis. Important though is the idea that if there was a large-scale loss of ice sheet volume in the Pliocene, important evidence should be found in the marine sediment record. Thus, science turned to this are in search of further answers.

Marine sediments contain a compelling range of evidence in support of stability. The data collected and summarised in this paper is not consistent with a 66% loss in ice volume, 50 plus metre rise in sea level, and warming of surface water temperatures of 5° Celsius advocated by the instability hypothesis.

Greater attention now needs to be payed to better understanding and evaluating the Nothofagus find in the Sirius group. The assigned age for this geologic group needs to be re-examined. Similarly, alternative mechanisms of diatom deposition within the Sirius outcrop need to be established. Continued examinations of the fossils, looking to refine conditions in which it grew will also aid in further clarifying the nature of the Antarctic climate during the Pliocene.

Bibliography


