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Cover Page Footnote

Ph.D. in Geology. Assistant Professor to Full Professor, The Florida State University, 1971-Present; Principal Investigator of the FSU Antarctic Marine Geology Research Facility, 1993- Present. See . This research is supported by U.S. National Science Foundation Grant OPP-9422893 and a JOI-USSAC post-cruise award. I thank especially my Ocean Drilling Program Leg 183 (Kerguelen Plateau) shipmates and the Team Members from the Cape Roberts Project for many stimulating and helpful discussions on this subject. Peter Barrett (Victoria Univ.) and David M. Harwood (Univ. Nebraska) kindly provided important references and figures, and Reed Scherer (Univ. Northern Illinois) made available an important preprint of his work David Davenport helped modify the figures and the Journal staff provided diligent and in-depth editorial assistance.

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THE ANTARCTIC ICE SHEET: RISE AND DEMISE?

SHERWOOD WILLING WISE, JR.*

TABLE OF CONTENTS

I. INTRODUCTION**

Since 1995, the popular press has widely reported major break-outs of shelf ice along the Antarctic Peninsula as a harbinger of the deleterious effects of global warming.[1] Sections of the floating Larsen Ice Shelf the size of Rhode Island have detached and floated

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**Abbreviations for time in this article will be SI (International System of Units): ky = thousands of years; m.y. = millions of years; Ka = thousands of years before the Present; Ma = millions of years before the Present. Other abbreviations used in this article include: m = meters; ft = feet; *ca.* = circa; ~ = approximately; ‰ = parts per mil; $\delta^{18}O$ = oxygen isotope ratio; Gt/yr = gigatons per year; ODP = Ocean Drilling Program; CRP = Cape Roberts Project; CIROS = Cenozoic Investigations of West Ross Sea; IRD = ice-rafted debris; ANTOSTRAT = Antarctic Offshore Stratigraphy Program; DSDP = Deep Sea Drilling Program; SCAR = Scientific Committee on Antarctic Research.

1. *See generally* Charles W. Petit, *Polar Meltdown*, U.S. NEWS & WORLD REPORT, Feb. 28, 2000, at 64.

out to sea in a matter of days.[2] Indeed, since the mid-1940's the average annual temperature along the Antarctic peninsula has risen ~ 2° C (3-4° F) and in midwinter has risen 4-5° C (7-9° F).[3] This phenomenon has been accompanied by major dislocations of marine fauna which are sensitive to changes in temperature and ice conditions. For example, colonies of southern elephant seals and fur seals as well as gentoo and chinstrap penguins are moving south from the latitudes of the Falkland Islands to the vicinity of the U.S. scientific base at Palmer Station (Fig. 1).[4] On the other hand, the dominant Adélie penguins which reside there and feed on krill, are perishing.[5] On land, the normal low grasses, tiny shrubs and mosses of the tundra are thickening rapidly, glaciers are retreating, and major ice shelves are thinning.[6]

Although the annual temperatures farther south over the continent are not rising significantly, scientists are nonetheless concerned because Antarctica is considered to be the primary engine that drives ocean and atmospheric circulation in the Southern Hemisphere.[7] Any change in the condition or volume of its ice sheet could have profound effects not only on climate but on sea level as well. In a worst case scenario, if all of the water stored in the ice caps of the world were to melt, it would raise eustatic sea level 72 m (236 feet).[8]

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2. *See* Helmut Rott et al., *Rapid Collapse of Northern Larsen Ice Shelf, Antarctica*, 271 SCIENCE 788, 788-89 (1996). Other breakouts of shelf ice further south have also been reported within the last five years, including along the Ronne-Filchner Ice Shelf (*see* The Antarctic Meterological Research Center Photo Gallery [visited July 7, 2000] <http://uwamrc.ssec.wisc.edu/amrc/amrcgallery.html>) and the Ross Ice Shelf. In March 2000, the Ross Ice Shelf produced an elongate iceberg that measured 183 miles by 22 miles, about twice the size of the State of Delaware. The iceberg is believed to be "among the largest ever observed" and it will take approximately a century to replace. *See Huge Chunk of Ice Breaks Off From Antarctica Ice Sheet*, TALL. DEM., Mar. 24, 2000, at 4B (available from AP Wire Archives, Mar. 23, 2000 [visited Aug. 10, 2000] <http://llwire.ap.org>; *see* also Iceberg Images at Anarctic Meteorological Research Center (visited July 7, 2000) <http://uwamrc.ssec.wisc.edu/amrc/iceberg.html>.

3. *See* Jocelyn Kaiser, *Is Warming Trend Harming Penguins?*, 276 SCIENCE 1790, 1790 (1997).

4. *See id.*

5. *See id.* Krill are shrimp-like swimming organisms that must shelter under solid sea during their first month.

6. *See e.g.*, J. R. Potter & J. G. Paren, *Interaction Between Ice Shelf and Ocean in George VI Sound, Antarctica*, 43 ANTARCTIC RES. SERIES 35, 35-36 (1985). The base of the largest ice shelf in the western Antarctic Peninsula region, the George VI Ice Shelf, is melting at an average rate of 2 m/yr and is retreating at 1 km/yr. The Wordie Ice Shelf was historically a source of ice flowing into Marguerite Bay but has disappeared within the last two decades. *See generally* C. S. M. Doake & D. G. Vaughan, *Rapid Disintegration of the Wordie Ice Shelf in Response to Atmospheric Warming*, 350 NATURE 328, 328-29 (1991).

7. *See generally* A. B. Mullan & J. S. Hickman, *Meteorology*, 51 ELSEVIER OCEANOGRAPHY SERIES 21, 51 (1990).

8. *See* B.P. Flower, *Cenozoic Deep-Sea Temperatures and Polar Glaciation: The Oxygen Isotope Record*, 3 TERRA ANTARCTICA REPORTS 27, 29 (1999).

This rise would be enough to flood San Francisco's Golden Gate Bridge.[9] Lesser melt downs would be disastrous for most coastal cities and island nations of the world,[10] not to mention the southern halves of the states of Florida and Louisiana.[11]

The culprit, in the eyes of many, is global warming, perhaps induced by man's activities including the anthropogenic release of "greenhouse" gases.[12] These gases raise temperatures by trapping within the atmosphere long-wave (heat) radiation emitted by the sun-warmed Earth.[13] Records of the steady increase in these atmospheric gases have been kept only for the past three decades at the Mauna Loa Observatory in Hawaii.[14] Over the past two centuries, however, sharp increases in carbon dioxide of 30% and methane of 145% have been detected in gas bubbles trapped in cores from the Greenland Ice Sheet.[15] These values have never been experienced in the last 420,000 years for which ice-core records from ice sheets exist.[16] When combined, these curves paint a startling picture for the years after the beginning of the Industrial Revolution (Fig. 2) and peak at present day. In North America, the winters from 1997 to 2000 have been the warmest since the government began record keeping 105 years ago. This is apparently an El Nino-induced phenomenon,[17] although continued record temperatures and droughts around the world during the summer of 2000 led noted climatologist James Hansen of the Goddard Institute to observe "in

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9. *See Golden Gate Bridge*, WORLD BOOK ENCYCLOPEDIA 255 (2000) (stating that the floor of the bridge is 67 m (220 ft) above sea level).

10. *See* Nicholas D. Kristof, *For Pacific Islanders, Global Warming is No Idle Threat*, TALL. DEM., Mar. 2, 1997, at 16A (pointing out that "Kiribati, the Marshall Islands, and Tuvalu in the Pacific Ocean and the Maldives in the Indian Ocean" are mostly coral atolls only a few feet above sea level. In addition to inundating these nations, "a 1 m (3.3 ft) rise in sea level would force the evacuation of [some] 70 million Chinese and 32 million Bangladeshis. One-fifth of Bangladesh would disappear").

11. *See* Rick Callahan, *Greenland's Glaciers May be Biggest Threat*, TALL. DEM., April 9, 2000, at 14A; William K. Stevens, *Catastrophic Melting of Ice Sheet is Possible, Studies Hint*, N.Y. TIMES, July 7, 1998, at F4.

12. "Greenhouse" gases include carbon dioxide [CO_2], methane [CH_4], nitrogen oxide [N_2O], and the man-made chlorofluocarbons [CFCs].

13. *See* GRAHAM R. THOMPSON & JONATHAN TURK, MODERN PHYSICAL GEOLOGY 453-469 (2d ed. 1997).

14. *See Mauna Loa Observatory* (visited June 6, 2000) <http://mloserv.mlo.hawaii.gov/>.

15. *See* G. Orombelli, *Climate Record from Ice Cores*, 3 TERRA ANTARCTICA REPORTS 3, 9 (1999) (citing J. R. Petit et al., *Climate and Atmospheric History of the Past 420,000 Years from the Vostok Ice Core, Antarctica*, 399 NATURE 429 (1999); see Fig. 1 for the location of the Vostok core).

16. *See id.*

17. *See* Brigitte Greenberg, *La Nina Culprit Behind History's Warmest Winter*, TALL. DEM., Mar. 12, 2000, at 1A.; *see also U.S. Has Its Warmest January-April on Record, NOAA Reports* (last modified May 24, 2000) <http://www.noaanews.noaa.gov/stories/s432.htm>.

my opinion, we can say that global warming is contributing to the increased frequency of extreme events."[18]

Temperature increases are also being noted in the oceans where the average heat content to ~275 m (900 ft) has increased 0.56% from 1948 to 1996. Waters as deep as ~3050 m (10,000 ft) have gained an average of 0.06° C (0.11° F).[19] The United Nations-sponsored Intergovernmental Panel on Climate Change (IPCC) has stated that "the balance of evidence suggests that there is a discernible human influence on global" warming.[20] It further declared that a doubling of greenhouse gases could raise average global temperatures by approximately 1° to 3.5° C (2° to 6° F) over the next century.[21] This in turn would raise average sea level approximately 15 to 94 cm (6 to 37 in) by melting of polar glacial ice.[22]

Nevertheless, the extent that man's activities are influencing global climate is a matter of strong debate. Some believe that the underlying strength and magnitude of Earth's natural climate cycles are far greater than man's ability to alter them. They believe, therefore, the warming over the past century and a half since the end of the "Little Ice Age"[23] may have little to do with human activities. The Ad Hoc Committee on Global Climate Issues of the American Association of Petroleum Geologists states frankly that "there is no discernible human influence on global climate at this time."[24]

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18. Shanon Begley, *If you can't take the heat...*, NEWSWEEK, Aug. 7, 2000 at 64.

19. *See* H. Josef Hebert, *Researchers Find Even Deepest of Oceans Warning*, TALL. DEM., Mar. 24, 2000, at 1B.

20 *See* INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE IN 1995: THE SCIENCE OF CLIMATE CHANGE, at 5 (J. T. Houghton et al. eds., 1996).

21 *See id.* at 6.

22 *See* R.A. WARRICK ET AL., *Changes in Sea Level*, *in* CLIMATE CHANGE IN 1995: THE SCIENCE OF CLIMATE CHANGE 364 (J. T. Houghton et al. Eds., 1996).

23 The "Little Ice Age" was a global cooling episode between about 1400 and 1850 AD during which mountain glaciers all over the world advanced well beyond their present limits. *See* J. MURRAY MITCHELL, JR., ENERGY AND CLIMATE 53 (1977); *see also* H. H. Lamb, *Climatic Fluctuations*, 2 WORLD SURVEY OF CLIMATOLOGY 173, 177-178 (1969). *See generally* George H. Denton & Wibjorn Karlén, *Holocene Climatic Variations-Their Pattern and Possible Cause*, 3 QUATERNARY RESEARCH 155, 155, 201 (1973) (pointing out that the Little Ice Age was the last of five such Holocene events which seem to be part of a smaller scale cycle superimposed on larger-scale climate trends).

24 See Lee C. Gerhard & Bernold M. "Bruno" Hanson, *Ad Hoc Committee on Global Climate Issues: Annual Report*, 84 AAPG BULL. 466, 466 (2000). This report has resulted in a policy statement on climate change approved by the AAPG Executive Committee on behalf of the U.S. members of the association which argues that "[D]etailed examination of current climate data strongly suggests that current observations do not correlate with the assumptions or supportable projections of human-induced greenhouse effects." *Climate change* 20 AAPG EXPLORER at 6, at 8 (1999). *But see* R.C.L. (Chris) Wilson, *Wait on Proof (in "Readers' Forum")*, 21 AAPG EXPLORER 82, 82-83 (2000); Andrew H. Warrington, *Tactical Move?*, *id.* at 83 (both letter writers are international members of the AAPG pointing out omissions and deficiencies in the

Undeterred, the IPCC has issued a draft of their next five-year report (due out this year) stating unequivocally with even more confidence "that there has been a discernible human influence on global climate."[25] They base their opinion in part on the magnitude and abruptness of the 20th-century warming when scaled against temperature data for the past millennium recorded in tree rings, other sources, and the more recent instrumental record (Fig. 3).

Given the concern over anthropogenic climate effect, it is ironic that just twenty-five years ago leading geoscientists and climatologists were predicting that the Northern Hemisphere was not only poised to enter another glacial cycle, but that the cooling trend from the 1940s to the mid-1960s might even be leading up to that event.[26] Their prediction was based primarily on the fact that we are living in an interglacial period that is thought to be nearing its end.[27] For the past *ca.* 700,000 years, glacial-interglacial cycles have been paced by variations in the earth's orbital parameters.[28] Combined, these render a ~100,000 year period in which the interglacials span about 1/10 of each cycle, or about 10,000 years.[29] Our present-day interglacial interval (formally called the Holocene Epoch) has already endured almost that long. Assuming that "nature [is] left to her own devices with [no] interference from man", predictions by paleoclimatologists

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Committee's report while also expressing some degree of dismay if not trepidation. "AAPG's ... opposing the Kyoto Protocol [*see infra* note 25 below] points to an organization failing to face the challenges of the 21st century" [Warrington, *supra* at 83] and "If this [global greenhouse gas] experiment triggers a rapid reorganization of the climate system, proof might come too late for preventative action" [Wilson, *supra* at 83]).

25. Richard A. Kerr, *Draft Report Affirms Human Influence*, 288 SCIENCE 589, 590 (2000) (noting that this report should be available in time for consideration during final negotiations on the "implementation of the Kyoto Protocol for the reduction of [anthropogenic greenhouse] gas emissions"). For more on the Kyoto Protocol, see Hoong N. Young, *An Analysis of a Global CO_2 Emissions Trading Program*, 14 J. LAND USE & ENVTL. L. 125 (1998).

26. *See* MITCHELL, *supra* note 23, at 55; *see also* J. Murray Mitchell, Jr., *Carbon Dioxide and Future Climate*, ENVIRONMENTAL DATA SERVICE, March 1977, at 3, 4 (stating that global climate had been cooling since 1940, and that if continued, many places would reach ice-age levels only 700 years from now); [*Weather Experts Believe Ice Age Is On Way*, TALL. DEM., June 4, 1975, at 12A.]

27. *See* MITCHELL, *supra* note 23, at 53; Mitchell, *supra* note 26, at 4.

28. These orbital variations are frequently referred to as Milankovitch cycles and are detected by time-series analysis of variations in the sedimentary record (such as the spacing of laminations [varves], contrasting rock types, or changes in geochemical or magnetic properties). For an excellent historical summary and explanation of Milankovitch theory written in layman's language, *see generally* JOHN IMBRIE & KATHERINE PALMER IMBRIE, ICE AGES, SOLVING THE MYSTERY (1998).

29. *See generally* MITCHELL, *supra* note 23, at 53.

as to the onset of the next glacial cycle vary, but could exist within the range of a few thousand years.[30]

Interestingly, marine sediment records show that climate stability on millennial time scales during interglacials is generally high. This is true for the relatively mild interglacial in which now we live.[31] Hence, despite relatively minor variations such as the Little Ice Age, human civilization has developed within a period of remarkably stable climatic conditions. On the other hand, both the marine sediment and continental ice-core records show that over the past 110,000 years some changes in climate have been large, abrupt, and global.[32] Even as recently as 8,000 years ago, a brief intense cold event occurred after temperatures had risen close to current levels.[33] These abrupt switches in global climate seem to reflect drastic reorganizations (or even collapses) of the current thermohaline oceanic circulation system. The triggers for these are not well understood, although the Antarctic ice sheet is an important influence on that system. Professor Wallace B. Broecker concludes that:

> [t]here is surely a possibility that the ongoing buildup of greenhouse gases might trigger yet another of these ocean reorganizations and thereby the associated large atmospheric changes. Should this occur when 11 to 16 billion people occupy our planet [as has been pro-

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30. *See* Mitchell, *supra* note 26, at 4. Cooling could begin as soon as 700 years from now (*see* MITCHELL, *supra* note 23) with a substantial expansion of Northern Hemisphere ice during the next 5,000 years. *See* DR. JAMES D. HAYS, OUR CHANGING CLIMATE 84 (1979).

31. Not all interglacial periods are created equal, however. Marine isotope stages have been systematically numbered with even numbers for glacial and odd numbers for interglacial intervals. Marine isotope stage 11, which began at about 400 Ka, was a particularly mild interglacial and produced ice-free conditions in the North Atlantic for about 30-40 ky. *See* Jerry F. McManus et al., *A 0.5-Million-Year Record of Millennial-Scale Climate Variability in the North Atlantic*, 283 SCIENCE 971, 973 (1999).

32. *See generally* Wallace S. Broecker, *Thermohaline Circulation, The Achilles Heel of Our Climate System: Will Man-Made CO_2 Upset the Current Balance?*, 278 SCIENCE 1582, 1582 (1997) (citing Wallace S. Broecker & George H. Denton, *The Role of Ocean-Atmosphere Reorganizations in Glacial Cycles*, 53 GEOCHIMICA ET COSMOCHIMICA ACTA 2465 (1989); W. Dansgaard et al., *A New Greenland Deep Ice Core*, 218 SCIENCE 1273 (1982); W. Dansgaard et al., *Evidence for General Instability of Past Climate from a 250-kyr Ice Core Record*, 364 NATURE 218 (1993); P.M. Grootes et al., *Comparison of Oxygen Isotope Records from the GISP2 and GRIP Greenland Ice Core*, 366 NATURE 552 (1993); W. Dansgaard et al., *The Abrupt Termination of the Younger Dryas Climate Event*, 339 NATURE 532 (1989); K. C. Taylor et al., *The 'Flickering Switch' of Late Pleistocene Climate Change*, 361 NATURE 432 (1993)).

33. *See* Broecker, *supra* note 32, at 1586 (citing Richard B. Alley et al., *Holocene Climatic Instability: A Prominent, Widespread Event 8200 Yrs. Ago*, 25 GEOLOGY 483 (1997)).

> jected for the next century], it could lead to widespread starvation.[34]

To determine what man's influence has or has not been on global climate and to make predictions for the future, scientists must first understand both the causes and effects of secular climate cycles. Knowledge of the glacial history of Antarctica is the key to such an understanding, since the Antarctic ice sheet accounts for about 90% of current global ice volume. This paper will review the glacial history and current efforts to decipher it, dwelling on what is known, unknown, and disputed in our knowledge base, as well as implications for the future. This paper will also consider promising lines of attack to extend that knowledge base by further exploration in Antarctica, the most remote and inhospitable environment on Earth.

Part II will serve as a description of the present ice sheet on Antarctica. Part III will provide a brief history of that ice sheet as currently understood based on detailed and exhaustive technical accounts. Part IV will discuss the stability of the ice sheet on West Antarctica and its implications for global warming, and Part V will present the conclusions.

II. THE PRESENT DAY ICE SHEET

The Antarctic Ice Sheet covers some 13.6 million square kilometers or about 98% of the continent[35](Fig. 4). Hence, it is most difficult to study its history directly from geological deposits on land. Up to 4,776 m thick, the ice sheet averages over 2 kilometers in thickness and attains a maximum elevation of over 4,000 m.[36] It is divided by the Transantarctic Mountains, which project above the ice at many points and separate a relatively stable East Antarctic Ice Sheet that rests mostly on continental crust located above sea level[37] from an inherently less stable West Antarctic Ice Sheet. The West Antarctic Ice Sheet is relatively unstable because it is grounded in many places well below sea level in a series of marine basins.[38] It

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34. Broecker, *supra* note 32, at 1588.

35. *See* P. Barrett, *Antarctic Climate History Over the Last 100 Million Years*, 3 TERRA ANTARCTICA REPORTS 53, 53 (International School of Earth and Planetary Science) (citing David J. Drewry, *The Surface of the Antarctic Ice Sheet*, ANTARCTICA: GLACIOLOGICAL AND GEOPHYSICAL FOLIO (1983)).

36. *See id.*

37. *See id.*

38. *See id.*; *see also* J.R. Keys, *Ice*, 51 ELSEVIER OCEANOGRAPHY SERIES 95, 96 (1990).

also projects north of 65° South into warmer climes along the Antarctic Peninsula (Fig. 4).

The ice sheet moves plastically under its own weight towards the sea where it thins to give rise to floating ice shelves that extend beyond the grounding line.[39] These ice shelves (Fig. 1) are particularly extensive over the inland Ross and Weddell Seas as well as along the eastern margin of the Antarctic Peninsula (the Larsen Ice Shelf). Beyond that, conditions are still sufficiently cold during the winter months to cause sea water around the continent to freeze. This creates an ephemeral sea ice that may extend over 1000 km beyond the continental margin,[40] but which breaks up and melts during the summer months. The freezing seawater, which also undercoats the bottoms of the ice shelves, rejects salt back into the water column to form dense cold brines that sink to the bottom of the ocean. This contributes to the Antarctic Bottom Water, which is a current that moves northward to help drive global ocean circulation.[41]

The conveyer-belt-like movement of the Antarctic Ice Sheet seaward and renewal at its source by precipitation of snow accounts for its relatively young age of just over 400,000 years. Thus, the Antarctic Ice Sheet is a dynamic system, subject to variations in supply and wastage. Were its components to melt, the West Antarctic Ice Sheet would cause sea level to rise 6 m, whereas the East Antarctic Ice Sheet would raise sea level by ten times that amount.[42]

III. ICE SHEET HISTORY

Our direct knowledge of the history of the Antarctic Ice Sheet is skeletal at best because the ice sheet either obscures or erodes away the geological deposits and features needed to decipher that history. For these reasons, geoscientists have come to rely on various "proxy" or indirect records of global climate and Antarctic ice behavior based on their analysis of marine sediments deposited beyond the continent itself. These proxies include: 1) the character of sediments deposited in the Southern Ocean surrounding the continent, including the deposition of ice-rafted debris (i.e., sediment detritus deposited

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39. *See* Keys, *supra* note 38, at 95.

40. *See* Leanne K. Armand, *An Ocean of Ice – Advances in the Estimation of Past Sea Ice in the Southern Ocean*, 10 GSA TODAY, March, 2000, at 5, Fig. 3 (2000).

41. *See* Stanley S. Jacobs et al., *Origin and Evolution of Water Masses Near the Antarctic Continental Margin: Evidence from $H_2{}^{18}O/H_2{}^{16}O$ Ratios in Seawater*, 43 ANTARCTIC RES. SERIES 59, 75-77 (1985).

42. *See* Barrett, *supra* note 35, at 53.

by melting ice bergs); 2) changes in sea level; and 3) variations in the oxygen isotope compositions of calcareous microfossil skeletons, particularly those of planktonic and benthic foraminifers[43] that accumulate in deep sea sediments of the world's oceans. Sea-level changes and variations in oxygen isotope ratios[44] provide estimates of ice volume (Fig. 5). Oxygen isotope ratios can also be used to help estimate paleotemperatures. The application of these proxies is by necessity based on a number of assumptions and variables,[45] not all of which can be well constrained. However, they do provide a reflection of major events in the history of the Antarctic Ice Sheet. Confirmation of these events, though, can be provided best by direct physical evidence in the way of sedimentary deposits left by the ice sheet itself. However, as stated above, direct evidence is difficult to obtain and hence is largely a task for the new century.

North American and European geologists have long recognized a series of Northern Hemisphere continental glacial-interglacial cycles, now dated as beginning about 2.5 Ma (million years before present). These comprise the so-called "ice age" in which we live. The antiquity of Cenozoic[46] Antarctic glaciations, however, was not brought home until the scientific drill ship, *Glomar Challenger*, explored the Ross Sea in 1973. Through this effort, ice-rafted debris was recovered and cored dating back to 25 Ma.[47] Shortly thereafter a detailed paleotemperature curve revealed an overall global cooling of about 7° C during the Cenozoic.[48] This curve was based on oxygen isotope measurements of planktonic and benthic foraminifers in *Glomar Challenger* cores from the Subantarctic region.[49]

Major steps along the benthic foraminiferal curve (which are similar to that depicted in Fig. 5) were interpreted as thresholds that

43. Planktonic and benthic foraminifers are unicellular ameboid-like protists that live at the surface or bottoms of the oceans, respectively.

44. Oxygen isotope ratios are measured against a standard and expressed through a formula by the term $\delta^{18}O$.

45. For a discussion of these variables vis a vis oxygen isotopes, see Sherwood W. Wise, Jr. et al., *Paleogene Glacial History of Antarctica*, *in* CONTROVERSIES IN MODERN GEOLOGY 136-137 (1991).

46. The Cenozoic Era comprises the last 65 m.y. of geologic time, beginning with the extinction of the dinosaurs which reigned during the preceding Mesozoic Era. See Figure 5 for the sequence of 'epochs' or subdivisions of the Cenozoic time interval (Paleocene, Eocene, etc.).

47. *See generally* Dennis E. Hayes & Lawrence A. Frakes, *General Synthesis, Deep Sea Drilling Project Leg 28*, 28 INITIAL REP. DEEP SEA DRILLING PROJECT 927-928, 938 (1975).

48. *See* Nicholas J. Shackleton & James P. Kennett, *Paleotemperature History of the Cenozoic and the Initiation of Antarctic Glaciation: Oxygen and Carbon Isotope Analyses in DSDP Sites 277, 279, and 281*, 29 INITIAL REP. DEEP SEA DRILLING PROJECT 743, 751, 754 (1975); *see also* Barrett, *supra* note 35, at 54, 61.

49. *See* Shackleton & Kennett, *supra* note 48; *see also* Barrett, *supra* note 35, at 61.

signaled significant events in the formation of Southern or Northern Hemisphere ice.[50] Underlying this overall cooling trend were several factors including the position of Antarctica under the geographic South Pole, and the dispersal of the other southern continents away from Antarctica via plate tectonics (Fig. 6). Antarctica's position provided a base for the accumulation of a land-based ice cap. The dispersal of the other continents allowed for two things to happen - the opening of deep-water marine passageways ("gateways") to allow the establishment of the infinite Antarctic Circumpolar Current, and better access of the interior of the continent to sources of moisture for the precipitation of snow. The Antarctic Circumpolar Current thermally isolated the continent from warmer currents of the global ocean circulation. Its establishment occurred when Antarctica's final connections with Australia and South America were severed during the Eocene and Oligocene.[51]

A. *Late Paleocene Thermal Maximum (~55.5 Ma)*

The bottom-water temperature peak during the Late Paleocene Thermal Maximum (~11-13° C; Fig. 5) is a logical place to begin our narrative of the Cenozoic history of the Antarctic Ice Sheet.[52] This is mainly because at that point, as most investigators would agree, there was virtually no continental ice sheet in existence.[53] This was a high-water mark, both literally and figuratively, of the "Greenhouse world" that had prevailed since the preceding Mesozoic Era.[54] Evaporation in the tropics produced warm, dense, oxygen-poor salty waters that swept through the oceans to Antarctica and upset the steady-state ecological balance normally enjoyed by the bottom dwelling benthic foraminifers. Their extinction at this point was the greatest for these organisms in the past ninety million years.[55] This upset was especially sudden as deep-sea waters rose *ca.* 8.7° C in less than 6,000 years to about 18° C at ODP Site 690 on Maud Rise off

50. *See* James P. Kennett, *Cenozoic Evolution of Antarctic Glaciation, the Circum-Antarctic Ocean, and Their Impact on Global Paleoceanography*, 82 J. GEOPHYSICAL RES. 3843 (1977).

51. *See id.* at 3845; *see also* Peter F. Barker et al., *Weddell Sea Palaeoceanography: Preliminary Results of ODP Leg 113*, 67 PALAEOGEOGRAPHY, PALAEOCLIMATOLOGY, PALAEOECOLOGY 75-102 (1988).

52. *See* Flower, *supra* note 8, at 29 (citing K.G. Miller et al., *Tertiary Oxygen Isotope Synthesis, Sea Level History, and Continental Margin Erosion*, 2 PALEOCEANOGRAPHY 1 (1987)).

53. *See* Flower, *supra* note 8, at 29 (citing THOMAS J. CROWLEY & G. R. NORTH, PALEOCLIMATOLOGY (1991)).

54. *See* Flower, *supra* note 8, at 34.

55. *See* Flower, *supra* note 8, at 33 (citing Ellen E. Thomas, *Late Cretaceous - Early Eocene Mass Extinction in the Deep-Sea*, *in* GLOBAL CATASTROPHES 481-496 (1990)).

Antarctica (Fig. 1).[56] According to oxygen-isotope records, surface waters also warmed.[57]

Other such thermal events apparently continued into the early Eocene, while warm-water loving calcareous nannoplankton[58] continued to thrive in the surface waters around Antarctica.[59] No major boundaries based on temperature changes in surface water masses are evident within the region, which is an indication of relatively equable climates at this time. Where terrestrial sedimentary deposits of this age exist along the Antarctic Peninsula, it appears the land was well vegetated by southern temperate or more warmth-loving flora consisting of angiosperms (particularly the southern beech, *Nothofagus*), southern conifers, and ferns.[60] Parts of East Antarctica were apparently rather warm with seasonal rainfall which allowed winds to blow dust out to sea.[61]

A number of hypotheses have been advanced to account for the Late Paleocene Thermal Maximum. Major changes in the mode of ocean circulation must have occurred.[62] These changes were caused by a catastrophic emission of greenhouse gases connected with increases of volcanism[63] and the climate feedbacks associated with such releases.[64] This suggests the Late Paleocene Thermal Maximum

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56. *See* Flower, *supra* note 8, at 33 (citing James P. Kennett & Lowell D. Stott, *Abrupt Deep-Sea Warming, Paleoceanographic Changes and Benthic Extinctions at the End of the Palaeocene*, 353 Nature 225 (1991)). The paleo-water depth at this site was ~2,100 m. *See* Kennett & Stott, *supra* at 225.

57. *See* Flower, *supra* note 8, at 34.

58. Nannoplankton are golden-brown algae that produce calcareous nannofossils, the basic constituents of chalk.

59. *See generally* James J. Pospichal & Sherwood W. Wise, Jr., *Paleocene to Middle Eocene Calcareous Nannofossils of ODP Sites 689 and 690, Maud Rise, Weddell Sea*, 113 PROC. OCEAN DRILLING PROGRAM, SCI. RESULTS 613 (1990).

60. *See* J.E. Francis, *Evidence from Fossil Plants for Antarctic Palaeoclimates Over the Past 100 Million Years*, 3 TERRA ANTARCTICA REPORTS 43, 48 (1999) (citing R.A. Askin, *Late Cretaceous-Early Tertiary Antarctic Outcrop Evidence for Past Vegetation and Climates*, 56 ANTARCTIC RES. SERIES 61 (1992); H.M. LI, *Early Tertiary Palaeoclimate of King George Island, Antarctica – Evidence from the Fossil Hill Flora*, *in* RECENT PROGRESS IN ANTARCTIC EARTH SCIENCE 371 (1992)).

61. *See* Shipboard Scientific Party, *Site 690*, 113 PROC. OCEAN DRILLING PROGRAM, INITIAL REP. 183, 238-39 (1988).

62. *See* Flower, *supra* note 8, at 34 (citing Kennett & Stott, *supra* note 56; James P. Kennett & Lowell D. Stott, *Proteus and Proto-Oceanus: Ancestral Paleogene Oceans as Revealed from Antarctic Stable Isotopic Results, ODP Leg 113*, 113 PROC. OCEAN DRILLING PROGRAM, SCI. RESULTS 865 (1990)).

63. *See* Flower, *supra* note 8, at 34 (citing David Rea et al., *Global Change at the Paleocene/Eocene Boundary: Climate and Evolutionary Consequences of Tectonic Events*, 79 PALAEOGEOGRAPHY, PALEOCLIMATOLOGY, PALAEOECOLOGY 117 (1990); Timothy J. Bralower et al., *High-Resolution Records of the Late Paleocene Thermal Maximum and Circum-Caribbean Volcanism: Is There a Causal Link?*, 25 GEOLOGY 963 (1997)).

64. *See* Flower, *supra* note 8, at 34 (citing G. R. Dickens et al., *Dissociation of Oceanic Methane Hydrate as a Cause of the Carbon Isotope Excursion at the End of the Paleocene*, 10

may have witnessed a natural global experiment with an outcome similar in many respects to some of the worst-case scenarios now being postulated for man's new millennium.

B. Eocene (55-34 Ma)

As noted in Figure 5, the Eocene epoch witnessed a progressive decline in sea-bottom oxygen-isotopic paleotemperatures from the high-water mark of the Late Paleocene Thermal Maximum. The early Eocene was nearly as warm as the latest Paleocene. However, around the beginning of the middle Eocene (at approximately 49 Ma) a consistent increase of $\delta^{18}O$ is noted. This equates to a decrease in inferred paleotemperatures. Some investigators believe the first Cenozoic ice sheets appeared on Antarctica at this time.[65] Although sedimentologic evidence has been cited in a number of instances to suggest that ice rafting and/or deposition by glaciers punctuated the gradual decline in paleotemperatures during the middle to late Eocene, none of these have been accepted as conclusive evidence of ice deposition because of questions concerning the age dates or origins of the sediments.[66] Antarctica continued to support healthy temperate vegetation during this period although an increase in the predominance of *Nothofagus* in the Antarctic Peninsula (Seymour Island, Fig. 1) indicates "the onset either of cooler or more seasonal climates."[67]

C. Eocene/Oligocene Boundary Transition (~33.6 Ma)

Far more striking in the deep-sea oxygen isotope record is the *ca.* 1‰ $\delta^{18}O$ "shift" (i.e., a permanent deflection in the curve) at the

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PALEOCEANOGRAPHY 965 (1995); G. R. Dickens et al., *A Blast of Gas in the Latest Paleocene: Simulating First-Order Effects of Massive Dissociation of Oceanic Methane Hydrate*, 25 GEOLOGY 259 (1997)). *See also* Katz et al., *The Source and Fate of Massive Carbon Input During The Latest Palocene Thermal Maximum*, 286 SCIENCE 1531 (1999) (providing sedimentologic evidence for the massive release of biologic methane along the continental shelf off Florida (CODR site 1051) at ~5.5 Ma in response to a warming of deep waters).

65. *See* Elizabeth M. Kemp, *Tertiary Climatic Evolution and Vegetation History in the Southeast Indian Ocean Region*, 24 PALAEOGEOGRAPHY., PALAEOCLIMATOLOGY., PALAEOECOLOGY 169 (1978); Werner U. Ehrmann, *Implications of Sediment Composition on the Southern Kerguelen Plateau for Paleoclimate and Depositional Environment*, 119 PROC. OCEAN DRILLING PROGRAM, SCI. RESULTS 185, 195-98, 201 (1991).

66. For a review of questionable occurrences, see Sherwood W. Wise, Jr. et al., *Paleogene Glacial History of Antarctica in Light of Leg 120 Drilling Results*, 120 PROC. OF THE OCEAN DRILLING PROGRAM, SCI. RESULTS 1001 (1992)

67. *See* Francis, *supra* note 60, at 48 (citing Rosemary A. Askin, *Late Cretaceous-Early Tertiary Antarctic Outcrop Evidence for Past Vegetation and Climates*, 56 ANTARCTIC RES. SERIES 61 (1992); ROSEMARY A. ASKIN, *Eocene – Earliest Oligocene Terrestrial Palynology of Seymour Island, Antarctica*, *in* THE ANTARCTIC REGION: GEOLOGICAL EVOLUTION AND PROCESSES 993 (1997)).

Eocene/Oligocene boundary ("short term" curve, Fig. 5). This is the greatest such change in the entire Cenozoic record. Exactly what this dramatic shift signaled has been the subject of considerable debate and interpretation over the years, as is often found with proxy records no matter how detailed and informative they may be. Clearly delineated in the seminal study of subantarctic foraminifera by Nicholas J. Shackleton and James P. Kennett,[68] this break in the curve was interpreted as the initiation of the psychrosphere[69] and a pivotal event in the evolution of Cenozoic climates.[70] Initially, this $\delta^{18}O$ shift was thought to mark the formation of the first floating sea ice around Antarctica[71] and not the development of an actual ice sheet. Subsequent oxygen-isotope studies, however, suggested a major expansion of the Antarctic Ice Sheet.[72] The argument in favor of a major ice-sheet expansion revolved around the fact that if no ice sheet were present then the paleo-temperature equation for an "ice-free world" would result in deep-water paleotemperatures close to the freezing point of seawater (colder than is found in the deep sea today).[73] This is a circumstance not supported by other geological evidence. If temperatures had been close to freezing, one would expect to see evidence of a polar cryospheric (glacial-ice) regime similar to the present-day southern high latitudes. This was clearly not the case at the Falkland Plateau, the southernmost locality at which high oxygen-isotopic values had been measured in the lower Oligocene, but where the sediments contain none of the ice-rafted debris prevalent in modern-day deposits.[74] The assumption of a significant volume of ice on the continent, corrected for possible variations in salinity, produced more reasonable bottom-water temperatures.[75]

Confirmation of predictions of a major ice sheet on the continent by early Oligocene times came with a flurry of drilling activity that

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68. *See generally* Shackleton & Kennett, *supra* note 48.

69. The psychrosphere is the modern mode of thermo-haline ocean circulation, which is driven primarily by cold waters generated in the high latitudes. *See generally* Barrett, *supra* note 35, at 63 (citing James P. Kennett, *The Development of Planktonic Biogeography in the Southern Ocean During the Cenozoic*, 3 MARINE MICROPALEONTOLOGY 301 (1978)).

70. *But see* R. H. Benson et al., *Evidence from the Ostracoda of Major Events in the South Atlantic and World-Wide Over the Past 80 Million Years*, *in* SOUTH ATLANTIC PALEOCEANOGRAPHY 325, 333 (K. H. Hsu and M. J. Weissert, eds.) (1985) (arguing that the psychrosphere developed earlier, during the Eocene).

71. *See* Kennett, *supra* note 50, at 3853.

72. *See generally* Flower, *supra* note 8, at 29 (citing Miller et al., *supra* note 52).

73. *See id.*

74. *See* S. W. Wise et al., *Cenozoic Evolution of Polar Water Masses, Southwest Atlantic Ocean*, *in* SOUTH ATLANTIC PALEOCEANOGRAPHY 283, 294-304 (1985); *see also* Wise et al., *supra* note 45.

75. *See* Wise et al., *supra* note 45.

took place around the continent during the late 1980's (Fig. 1). This was accomplished by ice-based drilling in the Eastern Ross Sea (the CIROS project) and by the scientific drill ship *JOIDES Resolution* off East Antarctica in the Weddell Sea (Site 693), Prydz Bay (Sites 739 and 742), and on the outlying Kerguelen Plateau (Sites 738, 744 and 748; Fig. 7). The CIROS-1 hole was cored using a diamond-impregnated drill bit from a drilling rig set on the annual fast winter sea ice.[76] This was the first time this procedure had been attempted. Ice-rafted debris detected in lowermost Oligocene rocks was interpreted as coming from mountain outlet glaciers along the Transantarctic Mountains.[77] On the opposite side of the continent, drilling over the outlying Kerguelen Plateau also produced unmistakable evidence of ice-rafted debris[78] in conjunction with the lower Oligocene benthic-foraminiferal isotopic shift (Fig. 8). The shift at this site registered 1.2-1.3 ‰ $\delta^{18}O$.[79] Considering that large drop stones deposited by ice bergs had also been drilled in 33 Ma sediment along the Weddell Sea margin,[80] it was concluded that a major ice sheet had reached the margin of the continent at several widely separated points around Antarctica during the early Oligocene.[81] Although it may have been as extensive as the present-day ice sheet, it would not have been as cold. Instead, it was probably "temperate" and "wet-based" (i.e., warmer internal temperatures, more prone to rapid expansion and decay) in nature.[82] This is similar to the ice sheets of the Northern Hemisphere during the past two and one-half million years.[83] Being temperate in nature, it would not have been as stable as the present-day Antarctic Ice Sheet but rather subject to major advances, retreats, and decay. This ice sheet probably would have disappeared completely at some point during the Miocene.[84]

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76. Fast sea ice freezes in against the shoreline and remains attached to land until the summer breakup, thus it can provide an exceptionally stable drilling platform. *See generally* JOHN B. ANDERSON, ANTARCTIC MARINE GEOLOGY 19-20 (1999).

77. *See* P.J. Barrett et al., *Synthesis*, 245 DSIR BULL. N. Z. 241, 245-47 (1989).

78. *See generally* James Breza & Sherwood W. Wise, Jr., *Lower Oligocene Ice-Rafted Debris on the Kerguelen Plateau: Evidence for East Antarctic Continental Glaciation*, 120 PROC. OCEAN DRILLING PROGRAM, SCI. RESULTS 161 (1992).

79. *See* James C. Zachos et al., *Isotope and Trace Element Geochemistry of Eocene and Oligocene Foraminifers from Site 748, Kerguelen Plateau*,120 PROC. OCEAN DRILLING PROGRAM, SCI. RESULTS 839, 841 (table 1), 847 (figure 5) (1992).

80. *See* Wise et al., *supra* note 66, at 1009, 1012 (figure 12).

81. *See* Wise et al., *supra* note 45.

82. *See generally* Barrett, *supra* note 77, at 244; *see also* Keys, *supra* note 38.

83. *See generally* Barrett, *supra* note 77, at 244; *see also* Wise et al., *supra* note 66.

84. *See* Elizabeth M. Kemp & Peter J. Barrett, *Antarctic Glaciation and Early Tertiary Vegetation*, 258 NATURE 507, 508 (1975); Miller et al., *supra* note 52; David M. Harwood et al.,

Varying estimates have been formulated for the sea-bottom temperatures and ice volumes associated with the Oligocene ice sheet. As mentioned previously, these two variables of $\delta^{18}O$ readings are difficult to partition out as they both contribute to the signal provided by the benthic foraminiferal curve. Approximately 0.5 of the increase in isotopic values has been ascribed to ice volume increase (45-m eustatic sea level lowering). "The remaining 0.9 ‰ [was] attributed to deep-sea cooling of 3-4° C, about 30-40% of the total" cooling found in the Cenozoic.[85] Depending on what estimate of bottom-water temperatures and ice compositions are assumed, the ice volume could have been anywhere from half the size to greater than the size of the present-day sheet[86] (Fig. 8). A recent analysis employing an independent method to estimate paleotemperatures at a lower latitude drill site[87] suggested that the ~0.9 ‰ shift recorded there can be attributed almost entirely to the ice-volume effect.[88] This accords well with the absence of significant extinction among the benthic foraminiferal assemblages.[89] At the higher southern latitudes where the isotopic shift was greater, however, there were marked changes in the surface-water phytoplankton populations, which indicate cooling in the vicinity of the Antarctic continent.[90] Significant to the present discussion, the $\delta^{18}O$ increase is thought to have occurred quite rapidly in "less than 350,000 years, with the greatest change [in] the final 40-50 thousand years."[91]

Multiple Miocene Marine Productivity Events in West Antarctica as Recorded in Upper Miocene Sediments Beneath the Ross Ice Shelf (Site J-9), 15 MARINE MICROPALEONTOLOGY 91 (1989).

85. *See* Flower, *supra* note 8, at 34 (citing James C. Zachos et al., *Evolution of Early Cenozoic Marine Temperatures*, 9 PALEOCEANOGRAPHY 353 (1994); James C. Zachos et al., *High-Resolution (10^4 years) Deep-Sea Foraminiferal Stable Isotope Records of the Eocene-Oligocene Climate Transition*, 11 PALEOCEANOGRAPHY 251 (1996)).

86. *See generally* Flower, *supra* note 8, at 29 (citing Zachos et al. *Evolution of Early Cenozoic Marine Temperatures* (1994), *supra* note 85; Miller et al., *supra* note 52).

87. *See* Shipboard Scientific Party, *Site 522*, 73 INITIAL REP. DEEP SEA DRILLING PROGRAM 187, 187 (1984) (stating that Hole 522 was drilled at 26°6.843' S, 5°7.784' W in 4456.6 m of water).

88. *See* C. H. Lear et al., *Cenozoic Deep-Sea Temperatures and Global Ice Volumes from Mg/Ca in Benthic Foraminiferal Calcite*, 287 SCIENCE 269, 271 (2000).

89. *See generally* Ellen Thomas, *Middle Eocene-Late Oligocene Bathyal Benthic Foraminifera (Weddell Sea): Faunal Changes and Implications for Ocean Circulation*, *in* EOCENE-OLIGOCENE CLIMATIC AND BIOTIC EVOLUTION 245, 258-61 (Princeton University Press 1992).

90. *See* Wuchang Wei & Sherwood W. Wise, Jr., *Biogeographic Gradients of Middle Eocene-Oligocene Calcareous Nannoplankton in the South Atlantic Ocean*, 79 PALAEOGEOGRAPHY, PALAEOCLIMATOLOGY, PALAEOECOLOGY 29, 35, 46 (1990).

91. *See* Flower, *supra* note 8, at 34 (citing Zachos et al., *High-Resolution (10^4 years) Deep-Sea Foraminiferal Stable Isotope Records of the Eocene-Oligocene Climate Transition* (1996), *supra* note 85).

D. Oligocene-Early Miocene (34-15 Ma)

As previously mentioned, the early Oligocene isotopic shift is the "largest step in the transition from the 'greenhouse' to the 'icehouse' world" of the Cenozoic and has been numbered as the "Oi1" or first Oligocene benthic foraminiferal isotopic event (Fig. 5).[92] Following a change in the placement of the Eocene/Oligocene boundary and a recalibration of the geological time scale,[93] "Oi1" is now dated at 33.6 Ma.[94] Thereafter began a general warming trend of about sixteen million years punctuated by a number of intermittent glaciations on Antarctica as noted in ice-based drill cores[95] (CIROS-1, CRP; Fig. 1) and the deep-sea isotopic record.[96] Detailed studies are beginning to show that the intensity of some of these glaciations at least was modulated by variations in the Earth's orbital parameters, ie., Milankovitch cycles.[97]

By the late Oligocene, alpine (mountain valley) glaciation along the Transantarctic Mountains had given way to full-scale development of several ice sheets in East Antarctica that advanced repeatedly over the CIROS-1 locality. Upper Oligocene glacial deposits at CIROS-1 in the Eastern Ross Sea consist of a "number of thin (10's of m) till sheets [sediments deposited directly by glaciers] separated by thin mudstones that" represent interglacial intervals.[98] One of the latter contained a complete leaf impression of the southern beech, *Nothofagus*[99] along with contemporaneous pollen[100] that suggest a

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92. *See* Flower, *supra* note 8, at 31 (citing Kenneth G. Miller et al., *Cenozoic Global Sea Level, Sequences, and the New Jersey Transect: Results from Coastal Plain and Continental Slope Drilling*, 36 REVIEWS OF GEOPHYSICS 569 (1998)).

93. *See* William A. Berggren et al., *Towards a Revised Paleogene Geochronology, in* EOCENE-OLIGOCENE CLIMATE AND BIOTIC EVOLUTION 29 (1992); *see also* WILLIAM A. BERGGREN ET AL., *A Revised Cenozoic Geochronology and Chronostratigraphy*, GEOCHRONOLOGY, TIME SCALES AND GLOBAL STRATIGRAPHIC CORRELATION 129 (1995) (updating the time scale currently in use). For the previous widely used time scale, *see generally* William A. Berggren et al., *Cenozoic Geochronology*, 96 GEOLOGICAL SOC'Y AM. BULL. 1047 (1985).

94. *See* Flower, *supra* note 8, at 31, 36.

95. *See* Barrett et al., *supra* note 77. *See generally* Cape Roberts Science Team, *Initial Report on CRP-1, Cape Roberts Project, Antarctica*, 5 TERRA ANTARCTICA 1-187 (1998); Cape Roberts Science Team, *Initial Report on CRP-2, Cape Roberts Project, Antarctica*, 6 TERRA ANTARCTICA (1999); Cape Roberts Science Team, *Initial Report on CRP-3, Cape Roberts Project, Antarctica*, 7 TERRA ANTARCTICA 1-203 (forthcoming 2000).

96. *See* Benjamin P. Flower et al., *Milankovitch-Scale Climate Variability Recorded Near the Oligocene/Miocene Boundary*, 154 PROC. OCEAN DRILLING PROGRAM, SCI. RESULTS 433 (1997); James C. Zachos et al., *Orbitally Paced Climate Oscillations Across the Oligocene/Miocene boundary*, 388 NATURE 567 (1997).

97. *See generally* Flower, *supra* note 96 *see also* Imbrie & Imbrie, *supra* note 28.

98. *See* Barrett, *supra* note 35, at 64.

99. *See id.* (citing R. S. Hill, *Fossil Leaf*, 245 DSIR BULL. N. Z., 143-144 (1989)).

cool to cold temperate terrestrial climate on the flanks of the adjacent Transantarctic Mountains.[101] The trees may have existed near sea level in refugia between ice fields, as coastal enclaves of vegetation that persisted through repeated phases of glacial advances.[102]

The relative mild climates of the early Miocene[103] were "terminated by a succession of $\delta^{18}O$ increases", the most prominent (Fig. 5) and rapid being the "Mi3" event at ~13.8 Ma.[104] Sea levels dropped about 50 m from about 16 to 12 Ma.[105] An increase of ice-rafted debris in Southern Ocean cores confirms a major expansion[106] and semi-permanent establishment[107] of the East Antarctic Ice Sheet during this time.

E. Middle Miocene to Pliocene (15-2 Ma)

Just how permanent the East Antarctic Ice Sheet has been over the past fifteen million years has become one of the most contentious questions debated today among Antarctic specialists. Early interpretations of the oxygen-isotope record suggested that the West Antarctic Ice Sheet was established by late Miocene times and that the full Antarctic Ice Sheet had essentially been in place since that time, operating in a polar mode (very cold internal temperatures) similar to the present-day ice sheet.[108] However, other early studies of marine Southern Ocean phytoplankton raised the possibility of an

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100. *See generally* D. C. Mildenhall, *Terrestrial Palynology*, 245 DSIR BULL. N. Z., 119-127 (1989).

101. *See* Barrett, *supra* note 77.

102. *See generally* Hill, *supra* note 99; *see also* Mildenhall, *supra* note 100.

103. *See* Kemp & Barrett, *supra* note 84.

104. *See* Flower, *supra* note 8, at 36 (citing Benjamin P. Flower & James P. Kennett, *Middle Miocene Ocean/Climate Transition: High-Resolution Oxygen and Carbon Isotopic Records from Deep Sea Drilling Project Site 588A, Southwest Pacific*, 8 PALEOCEANOGRAPHY 811 (1993); Benjamin P. Flower & James P. Kennett, *Middle Miocene Deepwater Paleoceanography in the Southwest Pacific: Relations with East Antarctic Ice Sheet Development*, 10 PALEOCEANOGRAPHY 1095 (1995)). As with the Oligocene, the major events of the Miocene portion of the stable isotope curve for benthic foraminifers have been numbered, the Mi3 being the third event from the bottom. The most prominent was ~1.0 ‰. The most rapid was less than 200,000 years.

105. *See* Flower, *supra* note 8, at 36 (citing James D. Wright et al., *Early and Middle Miocene Stable Isotopes: Implications for Deepwater Circulation and Climate*, 7 PALEOCEANOGRAPHY 357 (1992); Flower & Kennett, *Middle Miocene Ocean/Climate Transition: High-Resolution Oxygen and Carbon Isotopic Records from Deep Sea Drilling Project Site 588A, Southwest Pacific*, 8 PALEOCEANOGRAPHY 811 (1993)).

106. *See* Flower, *supra* note 8, at 36 (citing Detlef A. Warnke et al., *Miocene-Pliocene Antarctic Glacial Evolution: A Synthesis of Ice-Rafted Debris, Stable Isotope, and Planktonic Foraminiferal Indicators, ODP Leg 114*, 56 ANTARCTIC RES. SERIES 311 (1992)).

107. *See* Flower, *supra* note 8, at 36; *see also* Barrett, *supra* note 35, at 65.

108. *See* Kennett, *supra* note 50, at 3856-57.

early Pliocene warm interval during which the West Antarctic Ice Sheet may have collapsed.[109]

This argument was taken one step further with reports by Peter-Noel Webb and David M. Harwood of planktonic diatoms and large clusters of diatoms (up to ~ 100 microns in diameter) of various ages in pre-Quaternary continental glacial deposits. These glacial deposits comprise the Sirius Group of sediments high up in the Transantarctic Mountains (Fig. 4).[110] These authors suggested the deposits were emplaced by relatively warm ("wet-based" and therefore inherently unstable) ice sheets from East Antarctica that overtopped the mountains while moving toward the Ross Sea.[111] They believed the marine diatoms had been eroded by ice from sedimentary interior basins on East Antarctica that had been previously flooded by marine waters during major deglaciations of the Antarctic Ice Sheet.[112] These events occurred as late as ~2.8 Ma.[113] In their view, a true "polar" ice sheet ("dry-based", cold and stable)[114] like that on Antarctica today did not develop until about 2.5 Ma, the time major glaciations began in the Northern Hemisphere. Their concept of a major collapse of much of the Antarctic Ice Sheet during and before the Pliocene is now referred to as the "Dynamicist school of thought."[115]

The "Dynamicists" were soon opposed by the "Stabilists" who believed that a true polar ice sheet has existed over the continent continuously for the past fifteen million years.[116] They contend that

109. *See* Paul F. Ciesielski & Fred M. Weaver, *Early Pliocene Temperature Changes in the Antarctic Seas*, 2 GEOLOGY 511, 513-515 (1974).

110. *See* Barrett, *supra* note 35, at 65.

111. *See generally* P.N. Webb et al., *Cenozoic Marine Sedimentation and Ice-Volume Variation on the East Antarctic Craton*, 12 GEOLOGY 287, 289-90 (1984).

112. *See id.*

113. This date was given by the youngest diatoms present during the late Pliocene. *See generally* David M. Harwood, *Late Neogene Climatic Fluctuations in the Southern High Latitudes: Implications of a Warm Pliocene and Deglaciated Antarctic Continent*, 81 S. AFR. J. SCI. 239 (1985); *see also* Steven M. Bohaty & David M. Harwood, *Southern Ocean Pliocene Paleotemperature Variation from High-Resolution Silicoflagellate Biostratigraphy*, 33 MARINE MICROPALEONTOLOGY 241, 248-67 (1998) (where Pliocene peak warming intervals are identified at ~4.2, ~4.3, ~4.5, and ~3.6 Ma from proxy records of planktonic microfossil abundances on the Kerguelen Plateau (fig. 7)).

114. *See* ROGER LEB. HOOKE, PRINCIPLES OF GLACIER MECHANICS 5 (1998).

115. *See* Molly F. Miller & Mark C. G. Mabin, *Antarctic Neogene Landscapes – In the Refrigerator or the Deep Freeze,?* 8 GSA TODAY, April 1998, at 1-3.

116. *See* Michael L. Prentice & Robley K. Matthews, *Cenozoic Ice-Volume History: Development of a Composite Oxygen Isotope Record*, 16 GEOLOGY 963, 964-966; *see also* James P. Kennett & Peter F. Barker, *Latest Cretaceous to Cenozoic Climate and Oceanographic Developments in the Weddell Sea, Antarctica: an Ocean-Drilling Perspective*, 113 PROC. OCEAN DRILLING PROGRAM, SCI. RESULTS, 937, 952-960 (1990); George H. Denton et al., *Cainozoic History of the Antarctic Ice Sheet*, *in* THE GEOLOGY OF ANTARCTICA 365, 410-414 (R. J. Tingey, ed., Claredon Press 1991).

the marine diatoms found in the Sirius Group were either wind blown onto the exposed outcrops and therefore the Sirius deposits could be much older[117] or were deposited with ejecta from an extra-terrestrial bolide (meteor) impact occurring in the Southern Ocean about 2.15 Ma.[118] This contention is supported by the fact that diatoms may be exceedingly small and are notoriously subject to transport over long distances by wind. For example, non-marine and brackish species from Patagonia, South America, have been recovered in some quantity in ice cores at the South Pole.[119] Not well explained by eolian (wind) transport, however, is how marine diatoms, particularly those clumped together in large clusters or those too large to be entrained by wind, wound up within and not just on the surface of eroding outcrops of the Sirius Group.[120]

The Sirius Group contains a rather diverse set of thick glacial and stratified sediments (including those from fluvioglacial, glacial-marine, fiord, and lacustrine [lake] environments), that suggest many advances and retreats of inland ice through gaps in the Transantarctic Mountains.[121] A wide variety of well-preserved evidence[122] (e.g., twigs, leaves, moss, pollen, seeds, and insects) has been put forth to support warmer climates when these deposits were laid down. For example, the Beardmore Glacier area (Fig. 1) contains finger-sized pieces of mature but stunted *Northofagus* wood that suggest mean annual temperatures of -12°C,[123] which is about 20° C warmer than presently in that area.[124]

The main disputed issue is the age of the Sirius Group. The Stabilists, who cite bolide impacts and wind-blown origins for the diatoms located there, believe it is considerably older than proposed

117. *See* Miller & Mabin, *supra* note 115, at 3 (citing Lloyd H. Burckle & N. Potter, Jr., *Pliocene-Pleistocene Diatoms in Paleozoic and Mesozoic Sedimentary and Igneous Rocks from Antarctica: A Sirius Problem Solved*, 24 GEOLOGY 235, 236-238 (1996); A. P. Stroeven et al., *On Marine Microfossil Transport and Pathways in Antarctica During the Late Neogene: Evidence from the Sirius Group at Mount Fleming*, 24 GEOLOGY 727, 729-730 (1996)).

118. *See generally* R. Gersonde et al., *Geological Record and Reconstruction of the Late Pliocene Impact of the Eltanin Asteroid in the Southern Ocean*, 390 NATURE 357, 357-363 (1997).

119. *See* David D. Kellogg and Thomas B. Kellogg, *Diatoms in South Pole Ice: Implications for Eolian Contamination of Sirius Group Deposits*, 24 GEOLOGY 115, 116-118 (1996).

120. *See* David M. Harwood & Peter-Noel Webb, *Glacial Transport of Diatoms in the Antarctic Sirius Group: Pliocene Refrigerator*, 8 GSA TODAY, Apr. 1998, at 1, 4-8 (1998).

121. *See* Barrett, *supra* note 35, at 67.

122. *See, e.g.*, Allan C. Ashworth et al., *A Weevil from the Heart of Antarctica*, 5 QUATERNARY PROCEEDINGS 15 (1997).

123. *See* Barrett, *supra* note 35, at 67 (citing Francis, *supra* note 60).

124. *See id.*

by the Dynamicists.[125] The Stabilists also point to glacial, geomorphic, and paleoclimate data from the McMurdo Dry Valley region to suggest that cold polar desert conditions have prevailed there for many millions of years, at least since the middle Miocene. This would rule out a dynamic ice sheet and episodes of more temperate climate during that period.[126] The Stabilists point to unconsolidated, unweathered, and uneroded ash beds within the Dry Valleys as old as 4 to 15 Ma. The pristine condition of the ash beds seems to rule out chemical weathering in warmer, moister conditions that would have prevailed during interglacial climates.[127] In addition, space-age technology (cosmogenic exposure-age analyses) used to date rocks at the surface suggests exposure times of greater than four million years.[128] These arguments are formidable, and are held by some[129] to represent the majority view of the investigators who have examined the question.

A recent review summarizes well the issues under debate and introduces articles by proponents for both sides of the diatom-transport issues.[130] The matter is not yet settled, however, and proxy evidence from the world's oceans and ice-sheet modeling studies are cited as support for both points of view.[131] Evidence for early Pliocene warmth and/or sea level rise is documented from outcrops

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125. *See, e.g.*, Arjen P. Stroeven et al., *Atmospheric Transport of Diatoms in the Antarctic Sirius Group: Pliocene Deep Freeze*, 8 GSA TODAY, Apr. 1998, at 1, 4-5; *see also* Barrett, *supra* note 35.

126. *See* Denton et al., *supra* note 116, at 397-398; George H. Denton et al., *East Antarctic Ice Sheet Sensitivity to Pliocene Climatic Change from a Dry Valleys Perspective*, 75(A) GEOGRAFISKA ANNALER 155, 165-168 (1993).

127. *See generally* David R. Marchant et al., *Late Cenozoic Antarctic Paleoclimate Reconstructed from Volcanic Ashes in the Dry Valleys Region of Southern Victoria Land*, 108 GSA BULL. 181, 188 (suggesting that mean annual temperatures have been no more than 3°C above present at any time during the Pliocene); David R. Marchant et al, *Pliocene Paleoclimate and East Antarctic Ice-Sheet History from Surficial Ash Deposits*, 260 SCIENCE 667, 668-669 (1993); David R. Marchant et al., *Miocene Glacial Statigraphy and Landscape Evolution of the Western Asgard Range, Antarctica*, 75(A) GEOGRAFISKA ANNALER 303, 322-330 (1993); David R. Marchant et al., *Miocene-Pliocene-Pleistocene Glacial History of Arena Valley, Quartermain Mountains, Antarctica*, 75(A) GEOGRAFISKA ANNALER 269, 295-302 (1993); David R. Marchant & George H. Denton, *Miocene and Pliocene Paleoclimate of the Dry Valleys Region, Southern Victoria Land: A Geomorphological Approach*, 27 MARINE MICROPALEONTOLOGY 253, 267-269 (1996).

128. *See* Susan Ivy-Ochs et al., *Minimum ^{10}Be Exposure Ages of Early Pliocene for the Table Mountain Plateau and the Sirius Group at Mount Fleming, Dry Valleys, Antarctica*, 23 GEOLOGY 1007, 1008 (1995); Mark D. Kurz & Robert P. Ackert, *Stability of the East Antarctic Ice Sheet? New Chronological Evidence from Bennett Platform, Antarctica*, 78 EOS (TRANSACTIONS, AMER. GEOPHYSICAL UNION) S185 (1997).

129. *See* Barrett, *supra* note 35, at 65.

130. Miller & Mabin, *supra* note 115.

131. *See id.* at 2 (noting that among other evidence the same modeling study is cited as support by both sides, namely that of Philippe Huybrechts, *Glaciological Modelling of the Late Cenozoic East Antarctic Ice Sheet: Stability or Dynamism?*, 75(A) GEOGRAFISKA ANNALER 221 (1993)).

on Antarctica[132] and within the marine record elsewhere,[133] but a question remains as to whether the magnitude of such events was sufficient to account for a major meltdown of the Antarctic Ice Sheet. It has also been argued that the oxygen isotopic record does not record a major warming during the early Pliocene and that no change in ice-sheet volume has been recorded by the distribution of ice-rafted debris.[134] New ice-volume calculations, however, based on a newly developed and as yet low-resolution Mg-temperature curve, show a strong reduction in ice volume at this time.[135] As stated by proponents for the Dynamicist view, "it appears that there were brief intervals during the Pliocene when the refrigerator door was left open."[136]

F. *Quaternary (2.0-0 Ma)*

Regardless of the controversy over the early Pliocene stability of the Antarctic Ice Sheet, one would expect the last two million years of its history to be better understood from marine sediment records and, for the past ~400,000 years, from ice cores. As noted previously, deep-sea records, particularly those that record $\delta^{18}O$ paleotemperatures, indicate that the pattern of Quaternary ice-volume change is cyclical, having been modulated by variations in the Earth's tilt and the ellipticity of its orbit (orbital forcing).[137] Between about 900-700 Ka, a 100,000 year cycle corresponding to an eccentricity variation became dominant.[138] Northern Hemisphere ice sheets entered the picture at about 2.7 Ma, apparently in response to oceanic circulation changes induced by the closure of the Isthmus of Panama.[139] Most of

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132. *See generally* Francis, *supra* note 60, at 50 (citing Patrick G. Quilty, *The Pliocene Environment of Antarctica*, 130(2) ROYAL SOC. OF TASMANIA, PAPERS AND PROC. 1, 4 (1996)).

133. *See generally* D.T. Cronin & H. J. Dowsett eds., *Pliocene Climates*, 10 QUATERNARY SCIENCE REVIEW 115-296 (1991); PRISM PROJECT MEMBERS, *Middle Pliocene Paleoenvironments of the Northern Hemisphere*, PALEOCLIMATE AND EVOLUTION WITH EMPHASIS ON HUMAN ORIGINS 197-208 (1995); Richard Z. Poore and L. Cirbus Sloan eds., *Climates and Climate Variability of the Pliocene*, 27 MARINE MICROPALEONTOLOGY 1-326 (1996); Bohaty & Harwood, *supra* note 113.

134. *See* James P. Kennett and David A. Hodell, *Stability or Instability of Antarctic Ice Sheets During Warm Climates of the Pliocene?*, 5 GSA TODAY, Jan. 1995, at 1, 11-13.

135. *See* Lear et al., *supra* note 88, at 270 (fig. 1E).

136. *See* Harwood & Webb, *supra* note 120, at 7.

137. *See generally* Flower, *supra* note 8, at 39 (citing Cesare Emiliani, *Pleistocene Temperatures*, 63 J. GEOLOGY, 538-578 (1955)); *see also* IMBRIE & IMBRIE, *supra* note 28.

138. *See* Flower, *supra* note 8, at 38 (citing A. C. Mix et al., *Benthic Foraminifer Stable Isotope Record from Site 849 (0-5 Ma): Local and Global Climate Changes*, 138 PROC. OCEAN DRILLING PROGRAM, SCI. RESULTS 371, 375-379, 385-387 (1995)).

139. *See* Jan Backman, *Pliocene Biostratigraphy of DSDP Sites 111 and 116 from the North Atlantic Ocean and the Age of Northern Hemisphere Glaciation*, 32 STOCKHOLM CONTRIBUTIONS IN GEOLOGY 115, 128-32 (1979); *see also* Lloyd D. Keigwin, Jr., *Pliocene Closing of the Isthmus of*

the variation in global ice volume (about 80 to 90 % or 120 m of sea-level equivalent) has generally thought to have been dominated by Northern Hemisphere ice sheets.[140] During the last glacial maximum at ~ 20 Ka, sea level was about 120 m lower than that of today.[141]

The potential role of the relatively unstable West Antarctic Ice Sheet, however, has been cited recently as a wild card in this otherwise stable picture of the Antarctic Ice Sheet. Beneath 1,030 m thick ice at the fast-flowing Ice Stream B[142] (drill hole UpB, Fig. 1), some 700 km from the margin of the West Antarctic Ice Sheet, a deformable clay-rich glacial sediment (till) beneath the ice was sampled that yielded extinct diatoms along with isotopic data that showed that the fossils had been deposited in open-marine waters.[143] In other words, the ice at this location had disappeared, allowing an incursion of the sea at some time during the past 1.3 million years (possibly as recently as 400,000 years ago), presumably during an exceedingly warm interglacial period.[144] A wind-blown source for the diatoms was excluded because the sediments contained significant amounts of the cosmogenic radioactive isotope beryllium-10, which denoted deposition in the open sea.[145] According to glaciologists, a 700 km retreat would leave little room for an ice sheet.[146] That in turn leaves little doubt that the West Antarctic Ice Sheet collapsed and flooded the world's coasts at that time, a time perhaps not much warmer than today.[147]

Panama, Based on Biostratigraphic Evidence From Nearby Pacific Ocean and Caribbean Sea Cores, 6 GEOLOGY 630, 632-33 (1978).

140. This view, however, does not adequately take into account the less well understood contribution of the Antarctic ice sheet.

141. *See* Richard G. Fairbanks, *A 17,000 Glacio-Eustatic Sea Level Record: Influence of Glacial Melting Rates on the Younger Dryas Event and Deep-Ocean Circulation*, 342 NATURE 637-642 (1989).

142. Ice streams are routes along which the ice flows very rapidly, at approximately 400 m/yr at this locality, where the sediment surface is about 600 m below sea level. *See* Reed P. Scherer et al., *Pleistocene Collapse of the West Antarctic Ice Sheet*, 281 SCIENCE 82, 82 (1998) (citing Richard B. Alley et al., *Deformation of Till Beneath Ice Stream B, West Antarctica*, 322 NATURE 57, 58 (1986); D. D. Blankenship et al., *Seismic Measurements Reveal a Saturated Porous Layer Beneath an Active Antarctic Ice Stream*, 322 NATURE 54 (1986); Hermann Engelhardt et al., *Physical Conditions at the Base of a Fast Moving Antarctic Ice Stream*, 248 SCIENCE 57 (1990)).

143. *See* Scherer et al., *supra* note 142, at 84.

144. *See id.* at 84 (suggesting that the meltdown occurred during marine isotope stage [MIS] 11). *See generally* Reed Scherer, *Quaternary Interglacials and the West Antarctic Ice Sheet* (in preparation) (manuscript at 1, 4-5).

145. *See generally* Scherer et al., *supra* note 142, at 82, 84.

146. *See* Richard A. Kerr, *Signs of Past Collapse Beneath Antarctic Ice*, 281 SCIENCE 17, 17 (1998) (quoting Robert Bindschadler of NASA's Goddard Space Flight Center in Greenbelt, Maryland).

147. *See id.*

Other evidence of relatively warm interglacial conditions during the Quaternary has come to light during a recent fast-ice-based drilling project off the Transantarctic Mountains in the eastern Ross Sea. During the austral spring of 1997, the Cape Roberts Project (Fig. 1) cored a meter-thick shell bed dated between 1.15 and 0.86 Ma.[148] This shell bed contained an astounding variety of over sixty species of fossil marine invertebrates[149] as well as calcareous planktonic nannofossils called thoracospherids.[150] The latter prefer relatively warm conditions and do not inhabit these waters today.[151] Diatoms in the shell bed are mostly open-marine species. Essentially absent are the sea-ice inhabiting diatoms that currently pervade the site.[152] From this it is inferred that the environment in McMurdo Sound was much different from today.[153] It has been suggested that this also was a time of West Antarctic Ice Sheet collapse.[154]

IV. STABILITY OF THE WEST ANTARCTIC ICE SHEET

The recent studies previously cited call into question the stability of the West Antarctic Ice Sheet even during the relatively recent Quaternary times. As the world's only large ice sheet grounded with its margins well below sea level, it is vulnerable to collapse.[155] It has already lost two-thirds of its mass since the Last Glacial Maximum, which occurred some 21,000 years ago.[156] Its recent history has been reviewed by Oppenheimer, who concluded from its somewhat erratic behavior that it will likely disintegrate during the next 500-

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148. *See* S.M. Bohaty et al., *Quaternary Diatom Biostratigraphy and Paleoenvironments of the CRP-1 Drillcore, Ross Sea, Antarctica*, 5 TERRA ANTARCTICA 431, 436-438 (1998).

149. *See generally* Marco Taviani et al., *Pleistocene Macrofossils from CRP-1 Drillhole, Victoria Land Basin, Antarctica*, 5 TERRA ANTARCTICA 485, 485 (1998).

150. *See* Giuliana Villa & Sherwood W. Wise, Jr., *Quaternary Calcareous Nannofossils from the Antarctic Region*, 5 TERRA ANTARCTICA 479, 481-484 (1998).

151. *See id.* at 481-82.

152. *See* Bohaty et al., *supra* note 148, at 441.

153. *See id.* at 443.

154. *See* Scherer et al., *supra* note 142 (speculating that this apparent meltdown occurred during marine isotope stage (MIS) 12, about 900,000 years ago); *see also* R. P. Scherer, *Quaternary Collapse of the West Antarctic Ice Sheet: MIS 11, Yes, but was it a Unique Eve,,t?* (visited June 8, 2000) <http://www.agu.org/meetings/waisfm99.html> (search under "Scherer").

155. *See* R.B. Alley & I. M. Whillans, *Changes in the West Antarctic Ice Sheet*, 254 SCIENCE 959, 959 (1991); Douglas R. MacAyal, *Irregular Oscillations of the West Antarctic Ice Sheet*, 359 NATURE 29, 29 (1992); Robert Bindschadler, *West Antarctic Ice Sheet Collapse?*, 276 SCIENCE 662-63 (1997); R. A. WARRICK ET AL., *supra* note 22.

156. *See* Robert Bindschadler, *Future of the West Antarctic Ice Sheet*, 282 SCIENCE 428, 428 (1998).

700 years.[157] This will cause sea level rise to accelerate at the beginning of the 22nd Century.[158]

This doomsday scenario was painted by glaciologist Johannes Weertman of Northwestern University twenty-five years ago. He warned that the ice sheet would collapse quickly if the climate warms.[159] Weertman explained that even a slight warming-induced retreat of the ice's grounding line (where it begins to float off the bottom to form its fringing ice shelves) will move the grounding line into thicker ice. [160] "The thicker the ice, the faster it flows outwards and the faster it thins. The faster it thins, the sooner it floats, moving the grounding line even farther inward and accelerating a retreat" that could destroy the West Antarctic Ice Sheet in a century or two.[161] The effect on our coastal cities would be catastrophic.

Not all investigators agree. Some point out that the confinement of the major ice shelves within enclosed embayments such as the Ross Sea provides a modicum of stability, as does spotty resistance of the ice sheet's bed, which helps hold them together.[162] One modeling study (Fig. 9) suggests that Antarctic mean annual air temperature would have to increase by 9° C before major decay would take place. A rise of 5°C would even cause ice sheet growth.[163] However, a more recent modeling study suggests that a relatively minor increase in water temperature can offset the effects of increased ice accumulation that results in rapid ice sheet retreat during an early stage of climatic warming.[164]

Another recent study suggests that the Greenland Ice Sheet may be even more vulnerable to collapse than the West Antarctic Ice

157. *See* Michael Oppenheimer, *Global Warming and the Stability of the West Antarctic Ice Sheet*, 339 NATURE 325, 330 (1998).

158. *But see* Bindschadler, *supra* note 156, at 429 (presenting a projection based on other data that estimates the future lifetime of the West Antarctic Ice Sheet at 4,000-7,000 yrs).

159. *See* J. Weertman, *Glaciology's Grand Unsolved Problem*, 260 NATURE 284 (1976); *see also* Kerr, *supra* note 146, at 19.

160. *See* Kerr, supra note 146.

161. *See id.* at 19.

162. *See id.*

163. *See* Barrett, *supra* note 35, at 57 (citing P. Huybrechts, *Glaciological Modelling of the Late Cenozoic East Antarctic Ice Sheet: Stability or Dynamism,?* 75(A) GEOGRAFISKA ANNALER 221, 236 (1993) (concluding that field studies have suggested a modest rise in air temperature could increase marine evaporation and hence snow accumulation on Antarctica). *See, e.g.*, Eugene W. Domack et al., *Advance of East Antarctic Outlet Glaciers During the Hypsithermal: Implications for the Volume State of the Antarctic Ice Sheet Under Global Warming*, 19 GEOLOGY 1059, 1061 (1991) (citing T. Huybrechts & J. Oerlemans, *Response of the Antarctic Ice Sheet to Future Greenhouse Warming*, 5 CLIMATE DYNAMICS 93 (1990)).

164. *See* Roland C. Warner & W. F. Budd, *Modelling the Long-Term Response of the Antarctic Ice Sheet to Global Warming*, 27 ANNALS GLACIOLOGY 161, 163-66 (1998).

Sheet because of its closer proximity to the equator.[165] Like the West Antarctic Ice Sheet, it represents about 6-m sea level equivalent. The study concludes that during the previous interglacial between 110-130 thousand years ago, much of Greenland's ice melted, whereas the West Antarctic Ice Sheet was little affected. It is of little comfort, however, to know that the Greenland Ice Sheet might melt before the West Antarctic Ice Sheet, particularly if both were to collapse.

Because of the currently high equator-to-pole temperature gradient (the temperature difference between those two extremes), global warming would cause temperatures at both poles to rise much faster than global mean annual temperature. This is where man's influence may come into play most dramatically. Figure 10 depicts the episodic 7° C decline in global temperatures over the past one hundred million years estimated from the deep-sea oxygen isotope method with notes as to where Antarctic and Northern Hemisphere ice sheets probably first appeared. Superimposed above that and on a much shorter time scale, future temperature rise as a result of anthropogenic emissions of CO_2 and other greenhouse gases is plotted according to two scenarios. The first is a "restricted" mode in which emissions are limited to early 1990's levels (5 gigatons per year (Gt/yr)). The second is an "unrestricted" mode in which there are no restraints on emissions. If emissions are unrestricted, mean global temperatures are expected to rise around 1-3 ° C in the next one hundred years and twice that amount by the end of the following century.[166] Traced back in time, such temperatures were last experienced on the planet 12-14 and 35-40 million years ago, respectively.[167] These were the times of the advent of the first semi-permanent ice sheets on East Antarctica and of the inception of the East Antarctic Ice Sheet itself, according to paleoclimatologists.[168] Once the ice sheets are disposed of, these authors predict that continued greenhouse temperature change over the next few hundred years should result in climate perturbations "comparable to or exceeding any that have been reached in the last 600 million years."[169]

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165. *See generally* Kurt M. Cuffey & Shawn J. Marshall, *Substantial Contribution to Sea-Level Rise During the Last Interglacial from the Greenland Ice Sheet*, 404 NATURE 591, 591 (2000); *see also* Callahan, *supra* note 11.

166. *See* INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, *supra* note 20, at 6.

167. *See* Barrett, supra note 35, at 54 (citing Thomas J. Crowley & Kwang-Yul Kim, *Comparison of Long Term Greenhouse Projections with the Geologic Record*, 22 GEOPHYSICAL RES. LETTERS 933 (1995)).

168. *See id.*

169 *See id.*

V. CONCLUSIONS

Our knowledge of the history of the Antarctic Ice Sheet is limited in that it must rely heavily on proxy indicators of ice volume and temperatures rather than direct evidence from ice sheet deposits. Nevertheless, a sufficiently detailed picture of that history is coming into focus to provide an understanding of the major steps in its growth and evolution of when our planet went into "refrigeration," culminating in the current "ice ages" of the past two and a half million years. The geologic record over the past fifty-six million years provides clearly defined end points for that spectrum, ranging from the unglaciated "greenhouse" world of the Late Paleocene Thermal Maximum to the present-day "icehouse" world with its now "polar" (-20° C) Antarctic Ice Sheet.

Geoscientists strongly debate the details of this history as well as the causes and effects of volume changes of the Antarctic Ice Sheet. They constantly work to refine their data and expand their databases through the acquisition of new and more detailed records. This often requires the development of new technologies to acquire the necessary geologic sections from the field and to interpret these in the lab. Much work remains to be done, however, to satisfactorily define the historic record of the ice sheet and decipher its natural cycle.

Nevertheless, incomplete as our historical knowledge of the Antarctic Ice Sheet and past global climate cycles is, it does provide a basis for predicting the future under two scenarios:

1) If nature is left to take its course and the rather predictable orbital modulation of climate continues into the future as it has during the late Quaternary, one would expect the climate to move from the current interglacial mode into a glacial one within the next millennium or two.[170]

2) If man's loading of the atmosphere with greenhouse gasses continues unabated, then global temperatures will rise and deglaciation of Antarctica will be inevitable. In other words, man will run in reverse the global experiment[171] that nature has run over the past

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170. *See Mitchell*, *supra* note 23, at 53, 55, 58.

171. Man's own release of industrially produced greenhouse gases has been aptly labeled an "inadvertent experiment being performed on the atmosphere by human activities" by V. Ramanathan. *See* V. Ramanathan, *The Greenhouse Theory of Climate Change: A Test by an Inadvertent Global Experiment*, 240 SCIENCE 293, 294 (1988).

fifty-five million years. The path that process would take is indicated by backtracking the geologic history of the Antarctic Ice Sheet (e.g., Fig. 10),[172] which is best done with the aid of computer modeling.[173] Not all conditions would be the same, however, in that the configuration of the continents has changed considerably over those fifty-six million years. Also, plants have evolved new types of vegetative covers such as grasses, and the composition of the atmosphere has not remained constant through time; i.e., a different set of boundary conditions exist now as opposed to then. Many of these factors, however, can be taken into account in the modeling.[174]

To improve computer models as well as our own understanding, scientists need more direct and detailed evidence of the behavior of the Antarctic Ice Sheet.[175] This, however, is a difficult record to obtain due to the logistics of working in this remote and inhospitable region where operational costs are high relative to other parts in the world. New technologies have to be developed to overcome these logistical difficulties. Tantalizing geologic records are known to exist around the margins of the continent where prograding sedimentary sequences deposited during past advances and retreats of the ice sheets have been imaged by seismic stratigraphy.[176] This is a powerful technique that utilizes earth-penetrating sound waves to provide an x-ray-like cross section through sedimentary sequences (Fig. 11). Coring these sequences with conventional weight-driven piston and gravity cores has been frustrated by inability to penetrate over-consolidated sediments compacted by the more recent ice advances. As a result, pre-Quaternary sediments are seldom retrieved by this means. Drilling these sequences with the scientific drill ship has met with limited success due to the constant heave of the ship and the prevalence of glacial drop stones ("erratics") that limit core recovery and quality, although more such drilling has been proposed.[177] Fast-ice-based diamond coring, such as that used by the recently

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172. *See* Huybrechts, *supra* note 163; *see also* Warner & Budd, *supra* note 164.

173. *See* Robert J. Oglesby, *Use of Climate Models to Extend Paleoclimatic Data*, 3 TERRA ANTARCTIC REPORTS 131 (1999).

174. *See id.*

175. *See* Peter N. Webb & Alan K. Cooper eds., *Antarctic Late Phanerozoic Earth System Science*, 16 SCAR ANTARCTIC OFFSHORE STRATIGRAPHY PROJECT REPORT 1, 1 (1999).

176. *See generally* Barrett, *supra* note 35, at 63 (citing Alan K. Cooper et al. eds., *Geology and Seismic Stratigraphy of the Antarctic Margin*, 68 ANTARCTIC RES. SERIES 1 (1995)); *see also* Alan K. Cooper et al., *Cenozoic Prograding Sequences of the Antarctic Continental Margin: A Record of Glacio-Eustatic and Tectonic Events*, 102 MARINE GEOLOGY 175, 177-79 (1991).

177. *See generally* Peter F. Barker et al., *Ice Sheet History from Antarctic Continental Margin Sediments: The ANTOSTRAT Approach*, 5 TERRA ANTARCTICA 737, 747, 756 (1998); *see also* Webb & Cooper, *supra* note 175, at 1, 3, 8.

completed Cape Roberts Project, has consistently provided high quality cores with an average 95% recovery during that expedition.[178] Fast sea ice, however, is found over only a limited number of basins that contain the right strata needed to answer the outstanding geologic questions. The adaptation of diamond coring techniques for use on ice-strengthened and ice-breaker vessels is still under development,[179] although suitable systems should become available for routine use during the coming decade.[180] Concerted efforts are also planned to purposefully sample sediments and bedrock beneath the existing ice sheets, although such operations face their own technical difficulties that need to be overcome.

In short, polar science is high risk and needs to be planned within a broad, long term framework that takes into account the logistical difficulties of working in these regions. An omnipresent logistical factor that complicates such work is the vagary of the polar weather. During the first year of the Cape Roberts Project, an early season storm forced cessation of drilling after only seven days of coring. The rig was nearly lost as the sea ice was broken up to within a kilometer of the drill site by incoming waves.[181] The project, however, enjoyed excellent ice conditions during its last two years when the sea ice platform was cold and thick. The final 940 m hole, a spectacular engineering feat in itself, was terminated only because the basal Cenozoic sediments (34 Ma in age) were reached above bed rock over ten times that age.[182] The same heavy sea-ice conditions that favored this type of drilling, however, severely frustrated contemporaneous efforts in Prydz Bay on the other side of the continent (Fig. 1) with the drill ship *JOIDES Resolution*. The ship was unable to reach several of its primary sites, which had been expected to yield

178. *See generally* Cape Roberts Science Team, *Initial Report on CRP-3, Cape Roberts Project, Antarctica*, 7 TERRA ANTARCTICA (forthcoming 2000) (manuscript at 201, 203 (Table 7.2)).

179. *See* Yngve Kristoffersen, *Approaches to Marine Shallow Drilling on the Antarctic Shelf*, 16 SCAR REPORT 39-40 (1999).

180. For a status report on the current state of technology, see G. L. Holloway, Report on Drilling Systems for Antarctic Research Vessels 49 (SHALDRILL Committee of Antarctic Earth Science Working Group) (1997) (unpublished report) (executive summary available on request from the Antarctic Marine Geology Research Facility, Florida State University).

181. *See* Cape Roberts Science Team (1998), *supra* note 95, at 127.

182. *See* Cape Roberts Science Team (2000), *supra* note 95, at 185. This project also benefitted from the use of state-of-the-art core description/processing equipment at the drill site and in a lab at McMundo Station (100 km to the south), such as a microwave acid-digestion unit for preparation of palynology samples (*see supra* note 181 at 22-23).

an older record of the East Antarctic Ice Sheet, possibly a record of its inception.[183]

Despite the logistical difficulties and setbacks, the future for Antarctic exploration to extend our understanding of ice sheet history is bright, considering international interest and commitment toward acquiring that knowledge.[184] All parties of the global change controversy recognize the need for sound baseline studies of nature's natural glacial cycles before man's potential role in influencing earth climate can be adequately assessed. The major question is whether we will gain that knowledge in time to make sound predictions for the future of the Antarctic Ice Sheet before the impact of man's activities is felt in an irreversible way.[185] The race is on.

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183. *See* Alan Cooper et al., 188 PROC. OCEAN DRILLING PROGRAM, INITIAL REP. (forthcoming 2001) (CD-ROM available from Ocean Drilling Program, Texas A&M Univ., College Station, TX 77845-9547). This ship also lacks the microwave digestion unit (*see supra* note 182), which severely limited shipboard analysis of pollen and spores, particularly during its most recent cruise to the Kenquplen Plateau (*see generally* Millard F. Coffin et al., 1983 Proc. Ocean Drilling Program, Initial Rep. (2000) (cd-rom available from Ocean Drilling Program, Texas A & M Univ., College Station, TX 77845-9547)).

184. *See generally* OCEAN DRILLING PROGRAM, LONG RANGE PLAN 1989-2002 (Joint Oceanographic Institutions, Inc., 1990); Webb & Cooper, *supra* note 175.

185. Ironically, by that time, one of the primary archives for the study of global warming, the ice sheet itself (and the ice cores that can be taken through it), will be gone.

APPENDIX

Figure 1. Antarctica, with locations of key features and areas mentioned in text. RIS – Ross Ice Shelf, LIS – Larsen Ice Shelf, RFIS – Ronne-Filchner Ice Shelf, MR – Maud Rise, KP – Kerguelen Plateau (Barrett, *supra* note 35, at fig. 10). UpB – upper ice stream B drill hole, CRP – Cape Roberts Project.

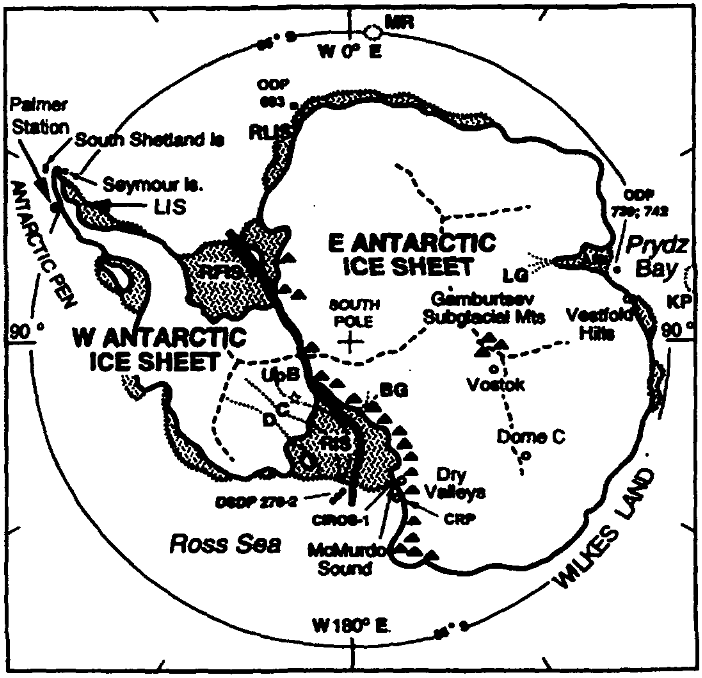

Figure 2. Increase of carbon dioxide and methane over the last two centuries based on analyses of air bubbles trapped in ice cores; solid lines denote instrument readings from the atmosphere (Orombelli, *supra* note 15 at fig. 7).

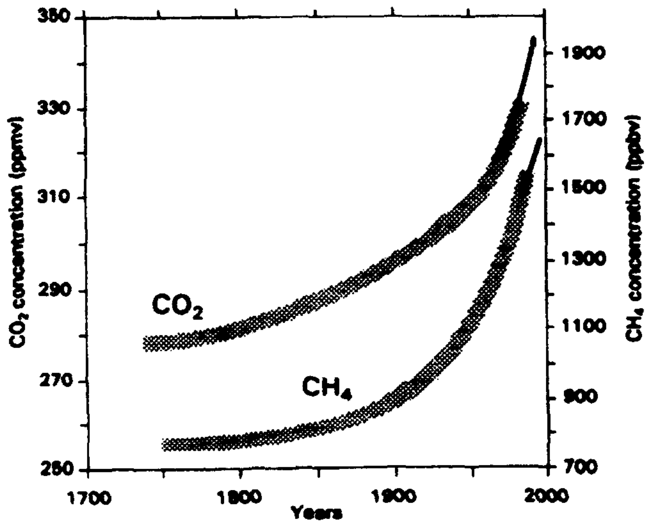

Figure 3. Global mean annual temperatures for the past 100 years based on tree-ring data and, for the past 200 years, ice core data and instrumented readings (Kerr, *supra* note 25).; *see also* Thomas J. Crowley, *Causes of Climate Change Over The Past 1000 Years*, 289 SCIENCE 270 (2000) (providing a detailed analysis of the data represented by this figure).

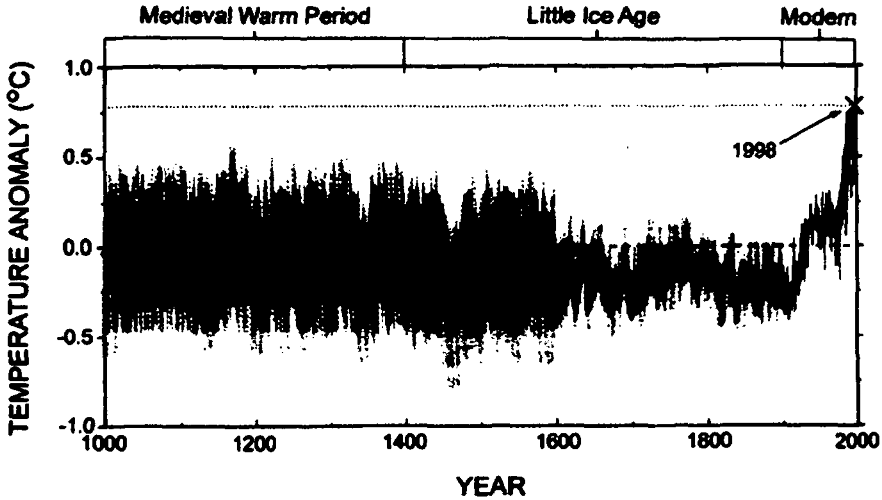

Figure 4. The Antarctic ice sheet today, with ice drainage patterns (elevations to the nearest thousand meters) and the main geographic regions of the continent (Barrett, *supra* note 35, at fig. 1, as adapted from Drewry, *supra* note 35). The East Antarctic Ice Sheet (60 m sea-level equivalent) is dammed on its west side by the Transantarctic Mountains, which separate it from the relatively less stable West Antarctic Ice Sheet (6 m sea-level equivalent) (Barrett, *supra* note 35).

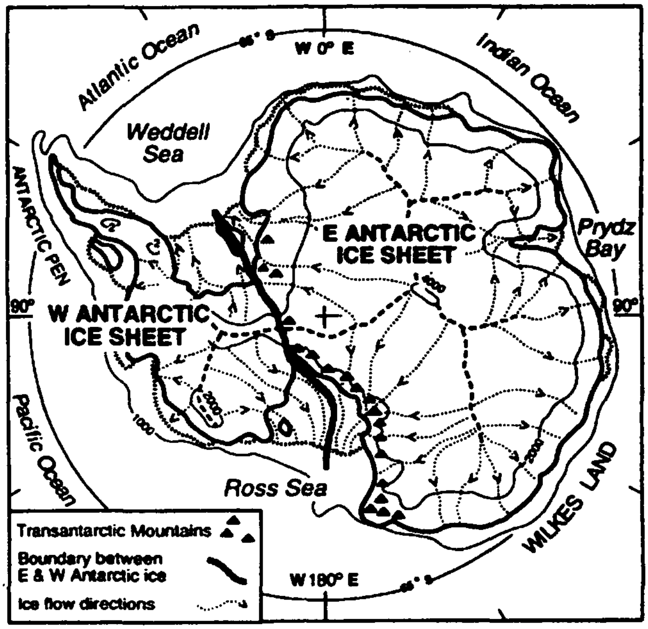

Figure 5. Two proxy indicators of ice sheet volume and/or sea bottom temperatures for the past 65 million years (Barrett, *supra* note 35 at fig. 9): 1) On the left, oxygen isotope rations ($\delta^{18}O$ expressed in parts per thousand [0/00%] for deep-sea benthic foraminifers from the Atlantic Ocean (Miller et al., *supra* note 52). The averaged long-term curve shows a steady increase in $\delta^{18}O$ values (= a fall in global temperatures and/or an increase in ice volume) beginning around the early Eocene, whereas the short-term curve denotes major steps such as the Oll and Mi3 events; 2) The curves to the right show variations in global sea levels from an independent method, seismic sequence analysis (Bilal U. Haq et al., *Chronology of Flucuating Sea Level Since the Triassic*, 235 SCIENCE 1156, 1159 (1987). This analysis shows a long-term fall in global sea levels since the early Eocene with short-term fluctuations, most of which are attributed to ice volume changes. The time scale is that of Berggren et al. (1985), which was superceded in 1995 (Berggren et al., *supra* note 93).

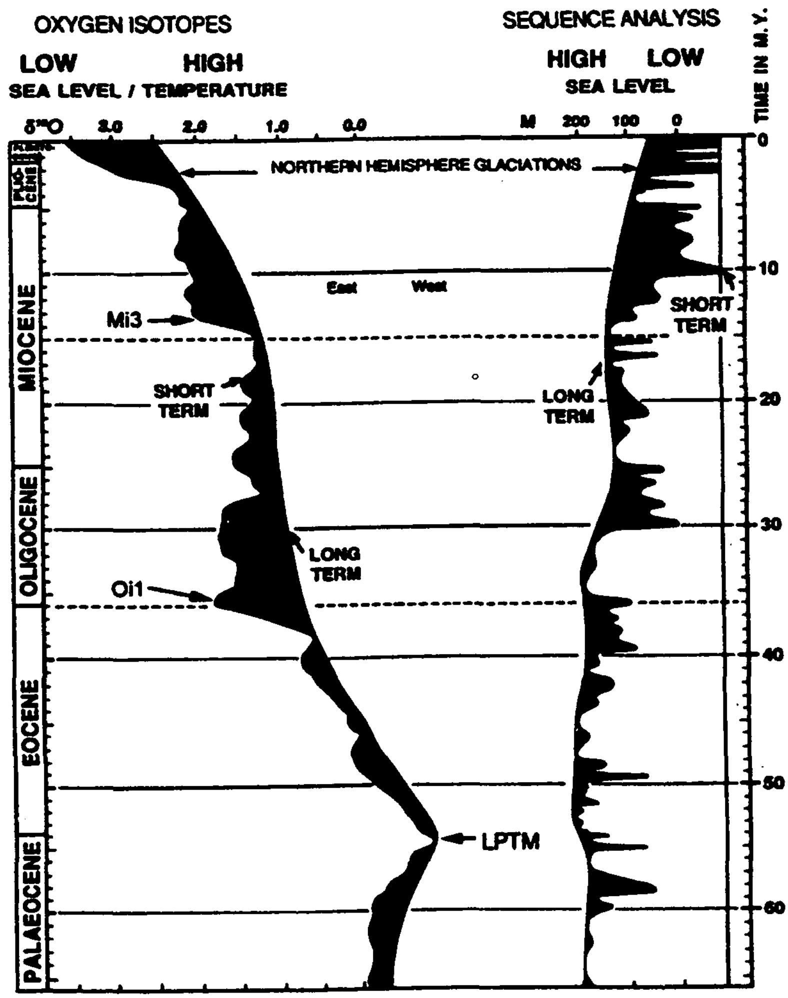

Figure 6. Dispersal of the Southern (Gondwana) continents away from Antarctica via plate tectonics ("continental drift"), resulting in its thermal isolation once all connections to Australia and South America were severed by earliest Miocene time and the deep-water circumantarctic current was established. At that point, oceanic currents from the equatorial regions could no longer bring warmth to Antarctica. Stippled areas show shallow shelves and shelf basins (Barrett, *supra* note 35, at fig. 4, as modified from Kennett, *supra* note 69).

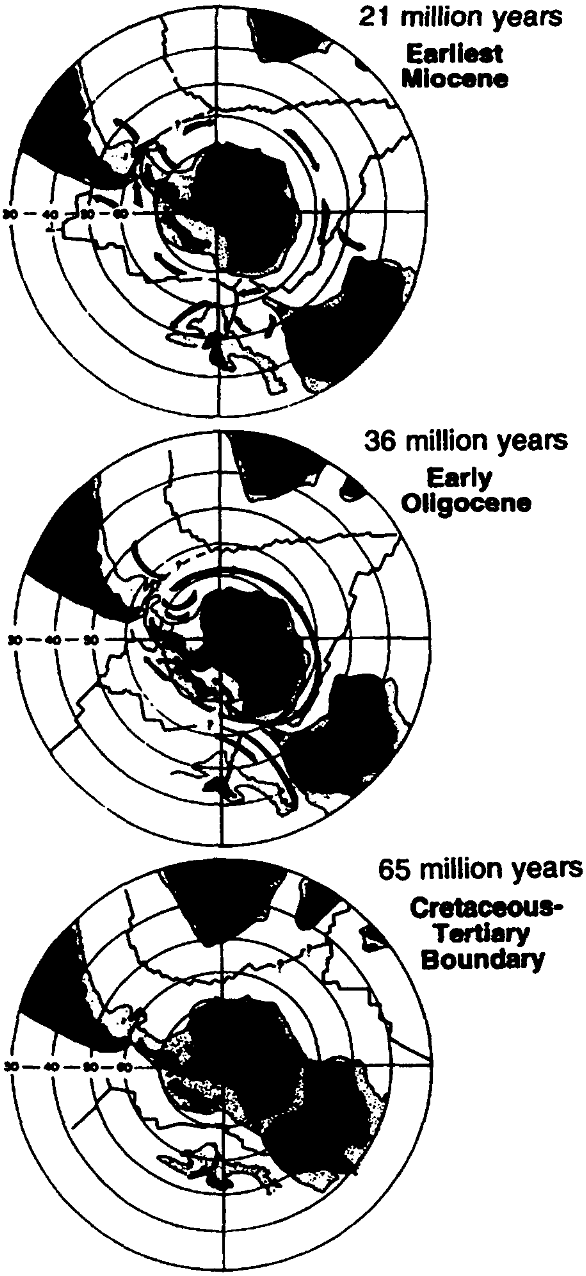

Figure 7. Paleogeographic reconstruction for the Prydz Bay region (see fig. 1) for the earliest Oligocene showing the advance of an East Antarctic Ice Sheet to sea level and the propagation of ice bergs that delivered ice-rafted debris to sites drilled by the Ocean Drilling Program on the Kergulen Plateau, some 1,000 km away (Wise et al., *supra* note 45, at fig. 8.18).

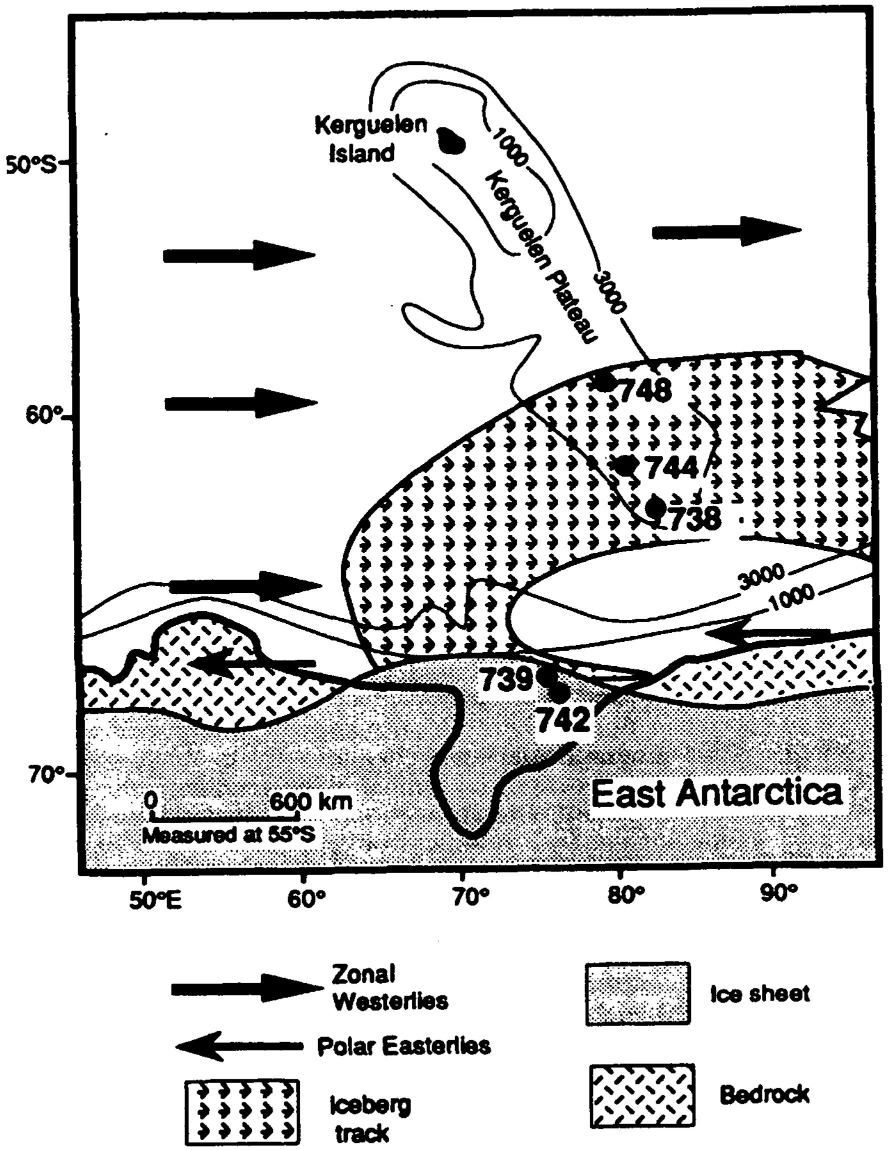

Figure 8. Summary of well-documented (solid pattern) and more speculative (unconfirmed; hatched-pattern) reports of middle Cenozoic glaciomarine sediments from Antarctic and Southern Ocean localities plotted against the record of deep-sea isotopic temperatures and global ice-volume (as a percentage of present-day ice-volume) computed from benthic foraminiferal oxygen isotope records. Two estimates of ice volume are given based on temperatures no colder than 1° C (black-shaded) and 1° to 4° C (hatched pattern) respectively; time scale (Berggren et al., *supra* note 93) (from James C. Zachos et al., *Abrupt Climate Change and Transient Climates During The Paleogene: A Marine Perspective*, 101 J. GEOLOGY 191, 196 (fig. 3) (1993)).

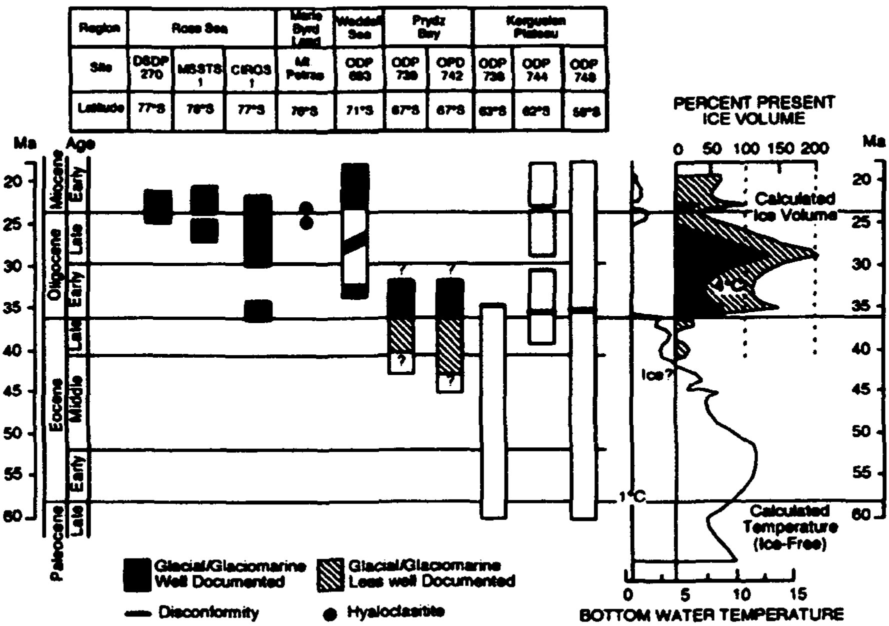

Figure 9. Maps and graph of ice-sheet size and location derived from a computer modal for mean-annual sea-level temperatures of 5, 9, 10, 15, 19, and 20° C above present-day values (Huybrechts, *supra* note 163).

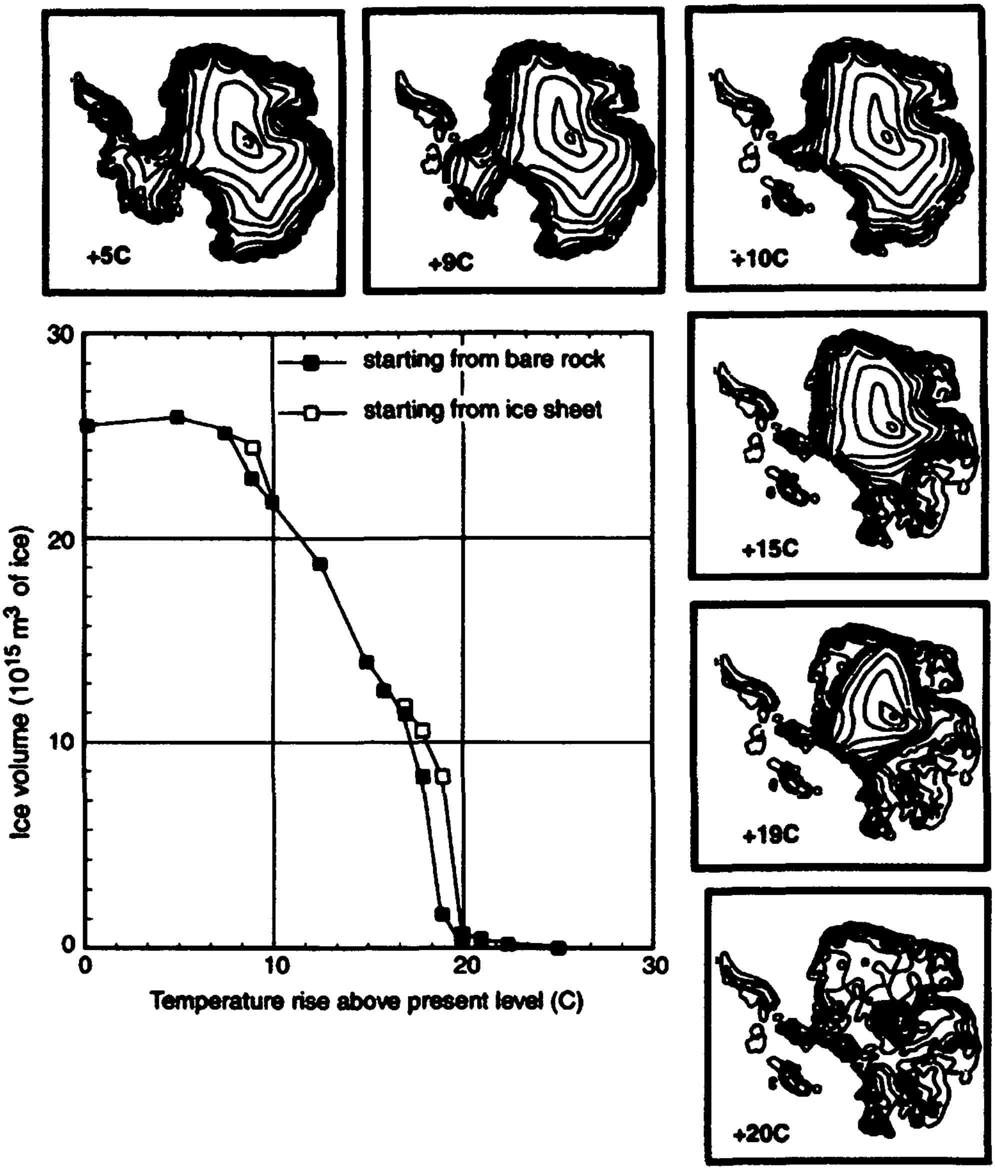

Figure 10. Changes in global temperature over the past 100 million years compared with that expected from future greenhouse warming over the next 2,000 years (Barrett, *supra* note 35, at fig. 2). The "restricted" scenario for the future assumes that CO_2 emissions to the atmosphere will be held to early 1900's levels (5 giga-tons per year), whereas the "unrestricted" curve assumes no restraints on emissions. The "unrestricted" (worst-case) scenario returns atmospheric temperatures to that of 12-13 million years ago by the end of this century and to the level last experienced 35-40 million years ago (when the Antarctic Ice Sheet first formed) by the end of 2200 A.D.

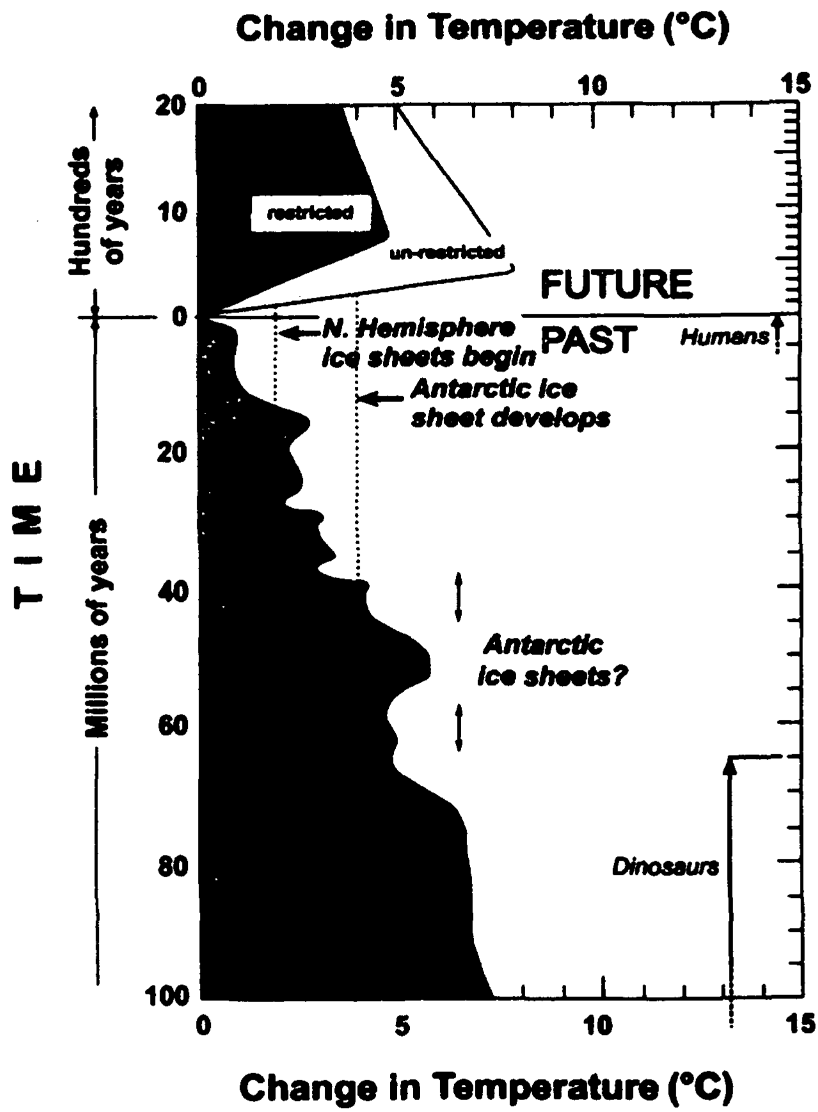

Figure 11. Seismic stratigraphic profile with interpretation (below) showing a cross-section of prograding glaciomarine strata on the Antarctic margin deposited during past advances and retreats of the ice sheets (Shipboard Scientific Party, *Leg 178 Summary: Antarctic Glacial History and Sea-Level Change,* 178 PROC. OCEAN DRILLING PROGRAM, INITIAL REP. 1, 44 (fig. F17) (Barker et al., eds.) (1999). This is one example of many such seismic sequences that await scientific exploration by high-quality diamond-coring techniques to be developed during the next decade.