Annals of Glaciology 3 1982

DID THE WEST ANTARCTIC ICE SHEET CREATE THE EAST ANTARCTIC ICE SHEET?

by

T. J. Hughes

(Department of Geological Sciences and Institute for Quaternary Studies, University of Maine at Orono, Orono, Maine 04469, U.S.A.)

ABSTRACT

The mostly terrestrial East Antarctic ice sheet is ten times larger and probably more stable than the mostly marine West Antarctic ice sheet. It is natural to suppose that the former appeared first, and that perhaps the latter was partially formed from an outflow of East Antarctic ice onto the West Antarctic continental shelf. Alternatively, the largely marine West Antarctic ice sheet may have appeared first, provided that post-Eocene continental drift allowed heavy snow precipitation over the West Antarctic island archipelago, but prevented warm South Pacific ocean currents from entering. Sea ice could then thicken and ground from surface accumulation and basal freezing, creating broad marine ice domes in shallow West Antarctic embayments. These marine ice domes could then merge with ice caps on the islands to create a marine ice sheet that could expand into East Antarctica and merge with highland ice caps to form the terrestrial East Antarctic ice sheet. A Cenozoic glacial history of Antarctica is outlined, based on this marine ice transgression hypothesis.

INTRODUCTION

The origin of the Antarctic ice sheet (Fig.1) has been discussed by Denton and others (1971), Mercer (1973, 1978), Drewry (1975, 1978), Shackleton and Kennett (1975), Kennett (1978), Kvasov and Verbitsky (1981), and many others. A consensus has not developed because there is no clear correlation between direct evidence (glacial erosion, ice contact deposits, and glacial marine sedimentation) and indirect evidence (sea-level changes and fossils used as paleoclimatic indicators), either from the Antarctic or from other parts of the world (notably New Zealand, Patagonia, and the Arctic). Lack of reliable dates is the major reason why attempts at correlations have remained tentative. Into this void, I would like to insert an Antarctic application of the "marine ice transgression" hypothesis developed by Denton and Hughes (1981) to explain the formation of Quaternary ice sheets in the Arctic. In an Antarctic application of this hypothesis, marine ice from West Antarctica would spread over East Antarctica and be the primary source of the East Antarctic ice sheet. The East Antarctic ice sheet has traditionally been viewed as primarily originating on plateaux in the presently subglacial Gamburtsev Mountains (Denton and others 1971) or in the Transantarctic Mountains (Mercer 1973, Drewry 1975). The traditional hypotheses are Antarctic applications of the "instantaneous glacierization" (Ives 1957, Ives and others 1975) and the "highland origin, windward growth" (Flint 1943, 1971) hypotheses for initiating the Laurentide and Scandinavian ice sheets, but without the time constraints. The Antarctic ice sheet could have formed over several Ma, but the Laurentide and Scandinavian ice sheets achieved their maximum size in less than 0.1 Ma.

THE MARINE ICE TRANSGRESSION HYPOTHESIS

John Mercer originated the concept of marine ice sheets in West Antarctica (Mercer 1968) and in the Arctic (Mercer 1970). Blake (1970) and Grosswald (1980) have presented the most compelling evidence for former marine ice sheets in the Arctic. The mostly marine West Antarctic ice sheet exists today. Crary (1958, 1960) has described how polar sea ice can become fast ice that thickens and grounds in the confined embayments and interisland channels of polar continental shelves. Wexler (1961) proposed that the West Antarctic ice sheet formed in this way, prior to formation of the East Antarctic ice sheet. In the marine ice transgression hypothesis, grounded sea ice becomes the domes of marine ice sheets and lowers highland snow-lines by increasing the regional albedo, thereby incorporating the essential features of the highland-origin, windward-growth, and instantaneous-glacierization hypotheses (Denton and Hughes 1981).

Figures 2 and 3 compare the physical settings of the Eurasian and West Antarctic ice sheets during their maximum Pleistocene extents. Both formed on broad continental shelves fringed by islands. How much marine ice originated from ice caps or mountain glaciers that spread from these islands into the confined embayments and interisland channels, and how much originated from grounded sea-ice, is unclear. What is clear is that Eurasian marine ice advanced southward onto a low plain that was unsuited for nucleating an ice sheet by the highland origin, windward growth, or instantaneous glacierization mechanisms. The southern margin of the Eurasian ice sheet advanced into warmer latitudes, where higher melting rates halted the advance.

West Antarctic ice spreading into East Antarctica would be entering the cold, dry climate expected for the interior of a polar continent. Melting along its margin would be minimal, so the advancing ice sheet would continue across East Antarctica until it reached the warmer coastal latitudes of Wilkes Land and Queen Maud Land where the ice sheet would either

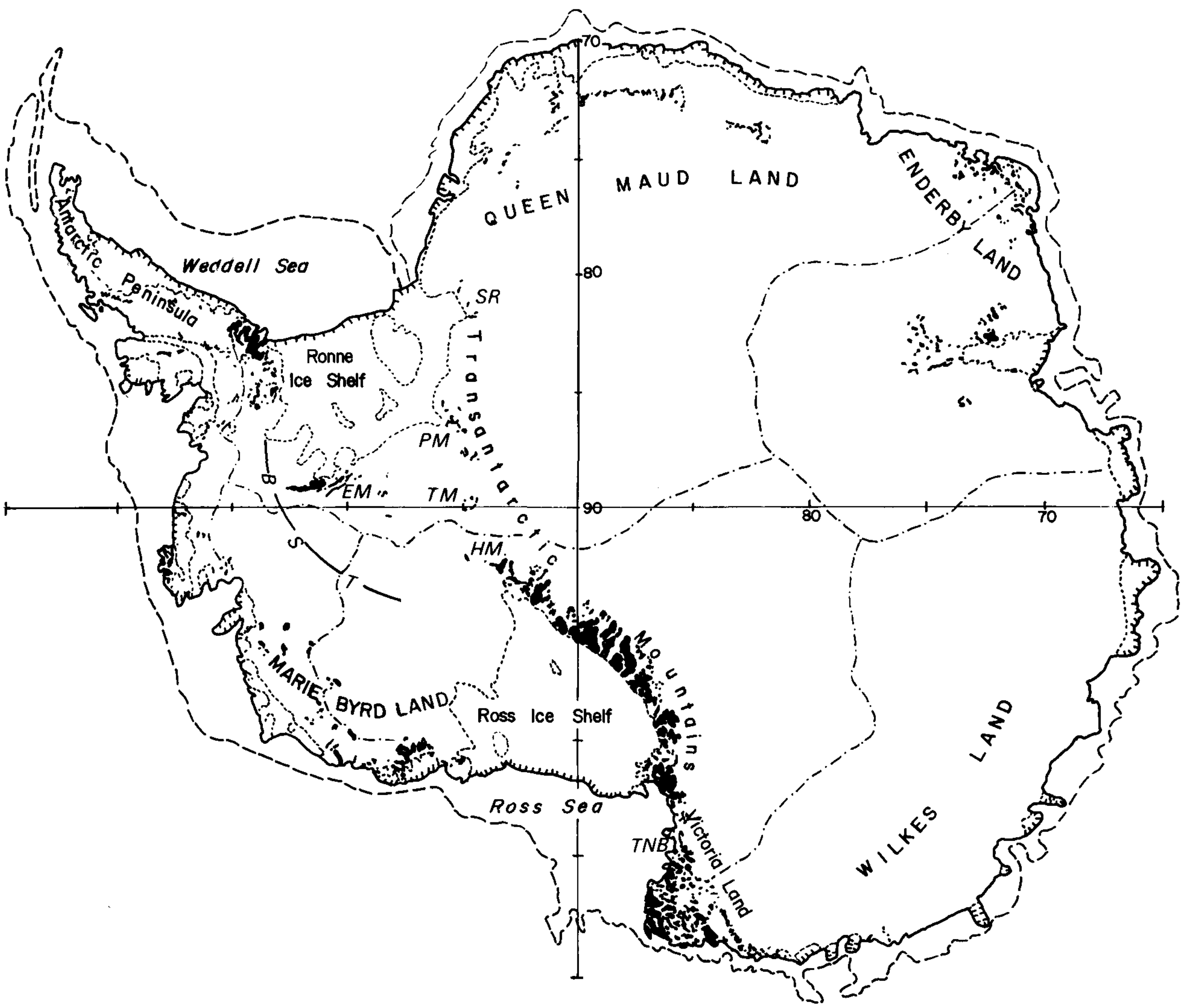

Fig.1. A location map of Antarctica. Shown are present coastlines (heavy solid line), continental shelf margin (heavy dashed line), ice divides (light dashed lines), ice-shelf grounding lines (dotted lines), ice-shelf calving fronts (hachured lines) and superglacial mountains (black areas). BST: Bentley Subglacial Trench, EM: Ellsworth Mountains, HM: Horlicks Mountains, PM: Pensacola Mountains, SR: Shackleton Range, TM: Thiel Mountains, TNB: Terra Nova Bay.

begin to melt, calve into the Southern Ocean, or merge with mountain glaciers that originated in coastal highlands. The West Antarctic ice divide would migrate into East Antarctica as the ice margin advanced. Katabatic winds flowing down the flanks of the ice divide, create the atmospheric low-pressure region over East Antarctica that draws in the "no cloud" precipitation of ice crystals nourishing much of the interior East Antarctic ice sheet today. Convective storms bring much heavier precipitation to the lower West Antarctic ice sheet.

Initiation of glaciation

Two assumptions underlie an application of the marine ice transgression hypothesis to Antarctic glaciation. First, water in the island archipelago of West Antarctica must have become cold enough to allow sea ice to become fast ice that thickened into an ice shelf that, in turn, grounded to form at least two broad marine ice domes on the continental shelf. Second, snow precipitation in West Antarctica, both before and after grounding, must have been substantially greater than the concomitant snow precipitation in East Antarctica, and must have resulted in a significant positive mass balance.

Figure 4 illustrates the requirements of the cold temperature and high precipitation assumptions. Antarctica was attached to Australia and South America (Smith and others 1973) and was apparently unglaciated (Denton and others 1971, Mercer 1973, 1978, Drewry 1975, 1978) about 50 Ma BP, during the Eocene. This grouping of Eocene continents made the South Pacific shoreline quite similar to the present-day North Pacific shoreline, which has not changed fundamentally since Eocene time. The Eocene arc of land extending from Indonesia around the North Pacific to Central America, broken only in the shallow Bering Sea and across Panama, would have continued around the South Pacific to New Guinea, again broken only in the shallow Ross Sea of West Antarctica. Consequently, we might expect that the present-day ocean currents and cyclonic storm tracks, both winter and summer, that influence temperature and precipitation on Arctic lands bordering the North Pacific (Chang 1972: 170-184), would have had quite similar Eocene counterparts on Antarctic lands bordering the South Pacific.

Temperature and precipitation over the islands of Marie Byrd Land in West Antarctica during the Eocene should have been comparable to present-day conditions over the Aleutian Islands of Alaska. This is a tundra environment with high winds and relatively heavy precipitation associated with the Aleutian low (Chang

1972: 226-228). Like the Bering Sea today, the Eocene Ross Sea would probably have had a winter cover of sea ice. Further to the east, however, the mountains of the Antarctic Peninsula and their Andean extension into Patagonia should have experienced the wetter but milder climate found along the partially glaciated Pacific slopes of mountains in southern and south-eastern Alaska.

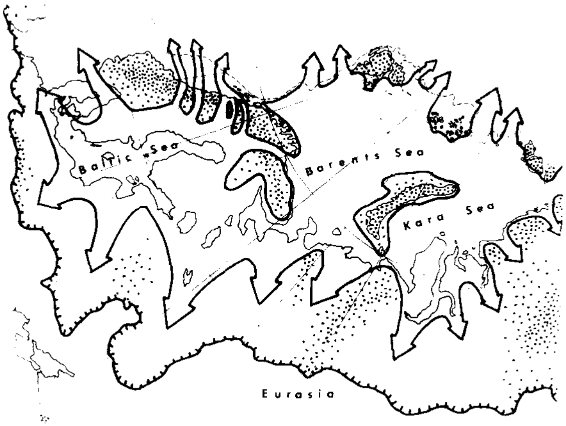

Fig.2. Eurasian glaciation according to the marine transgression hypothesis. Expanding glaciers from Arctic islands merge with thickening sea ice to create floating ice shelves that become successively grounded in the Kara, Barents, and Baltic seas. The grounded ice shelves become marine ice sheets with low, broad domes and the marine ice advances (arrows) to the edge of the continental shelf and onto adjacent land, surrounding and engulfing centers of terrestrial ice (dotted areas) on islands and in highlands. Melting halts the equatorward flow of ice across Eurasia.

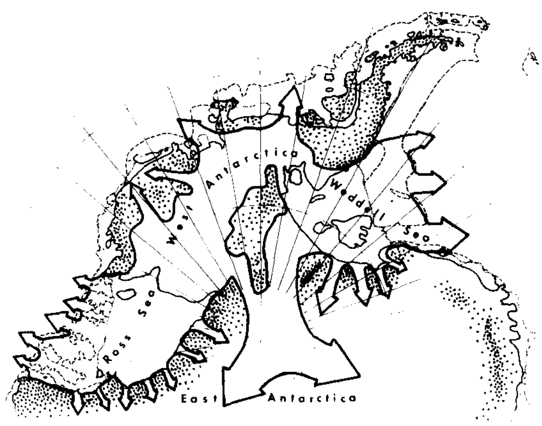

Fig.3. Antarctic glaciation according to the marine ice transgression hypothesis. Expanding glaciers from West Antarctic islands merge with thickening sea ice to create floating ice shelves that become successively grounded in the southern Weddell Sea beneath the present-day Filchner-Ronne Ice Shelf, the shallow southern part of the subglacial basin beneath the present-day grounded West Antarctic ice sheet, and the southern Ross Sea beneath the present-day Ross Ice Shelf. The grounded ice shelves become a marine ice sheet with low, broad domes lying east and west of the Ellsworth-Whitmore mountains massif. Marine ice from these domes advances (arrows) to the edge of the continental shelf and onto adjacent land, surrounding and engulfing centers of terrestrial ice (dotted areas) on islands and in highlands. The poleward flow of ice advancing across East Antarctica is not halted by melting.

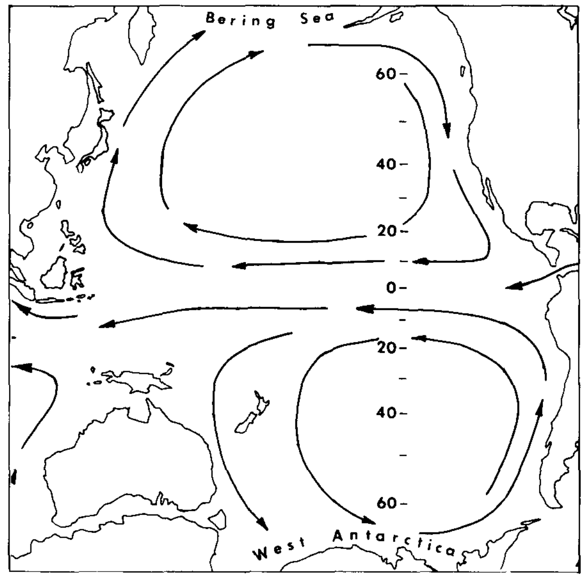

Fig.4. The nearly identical patterns of ocean surface currents in the North Pacific and the South Pacific during the Eocene. These currents, little changed today in the North Pacific, brought heavy Eocene precipitation to the Bering Sea and to West Antarctica. Outline of circum-Pacific continents is from Smith and others (1973).

Eocene East Antarctica would probably have had the kind of cold and dry continental climate found in north-eastern Siberia today. Even though north-eastern Siberia is similar to an unglaciated East Antarctica, being nearly surrounded by oceans and having extensive mountains and plateaux, present-day glaciation is minor (Krenke and Chernova 1980), and did not extend into lowlands even during the Wisconsin-Weichselian glaciation (Andersen 1981). Apparently, the few moisture-bearing convective storm systems that penetrate into north-eastern Siberia today (Chang 1972: 180-181) were even fewer during the last glaciation (Flint 1971: 74-75).

Rifting and sea-floor spreading, which isolated Antarctica from Australia (Kennett and others 1972) and South America (Dalziel and Elliot 1971), began about 53 Ma BP and the present-day Antarctic Circumpolar Current seems to have been established by 30 Ma BP (Kennett 1978). During this interval, the transformation in the direction and intensity of ocean and atmospheric circulation affecting Antarctica depicted in Figure 5 must have taken place. The most dramatic change occurred in West Antarctica. The Eocene South Pacific gyre was warmed as it passed through tropical latitudes northeast of Australia before it plunged southward into the West Antarctic island archipelago (Kennett and others 1972), bringing warm water and moisture-laden cyclonic storms. Today, the Antarctic Circumpolar Current is uniformly cold, only cold ocean gyres circulate in the seas of West Antarctica, the roaring westerlies drive the Antarctic Circumpolar Current, and the occasional cyclonic storms that penetrate the polar front bring precipitation mostly to West Antarctica (Weyant 1967: plate 10).

The transition from Eocene to present-day circulation patterns in the Antarctic, which were established during the Oligocene, may have included a time when moisture-laden cyclonic storms brought heavy snow-fall into West Antarctica, while the Antarctic Circumpolar Current prevented a concomitant infusion of warm ocean water. This would have been the time when the West Antarctic ice sheet could have formed by a combination of surface snow accumulation and basal ice freezing (Wexler 1961) which would have

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transformed Eocene seasonal sea-ice cover into Oligocene marine ice domes.

Direct evidence for Oligocene marine ice domes in West Antarctica is found in the abrupt ocean cooling recorded by oxygen isotope ratios 37 Ma BP in Campbell Plateau sea-floor sediments at Deep Sea Drilling Project (DSDP) Site 277 (Shackleton and Kennett 1975), the subglacial eruption of pillow lavas beginning 31 Ma BP in Marie Byrd Land (LeMasurier and Wade 1976), volcanic rocks having consistent dates that begin 24±12 Ma BP and lying on glaciated basement rocks in the Jones Mountains (Rutford and others 1972), and glaciomarine sediments at DSDP Site 270 in the Ross Sea (Frakes 1975). In discussing this dated direct evidence, Mercer (1978) and Drewry (1978) decide that the indirect biological evidence against a frigid Oligocene climate in West Antarctica is more compelling. However, newly formed marine domes would largely consist of frozen sea-water, which would never be much colder than -1.8°C and would not deplete the oceanic ^{16}O content, unlike terrestrial ice domes formed from snow-fall. I do not think that the direct and indirect evidence are necessarily in conflict, or that the Oligocene biological evidence rules out low marine ice domes in West Antarctica.

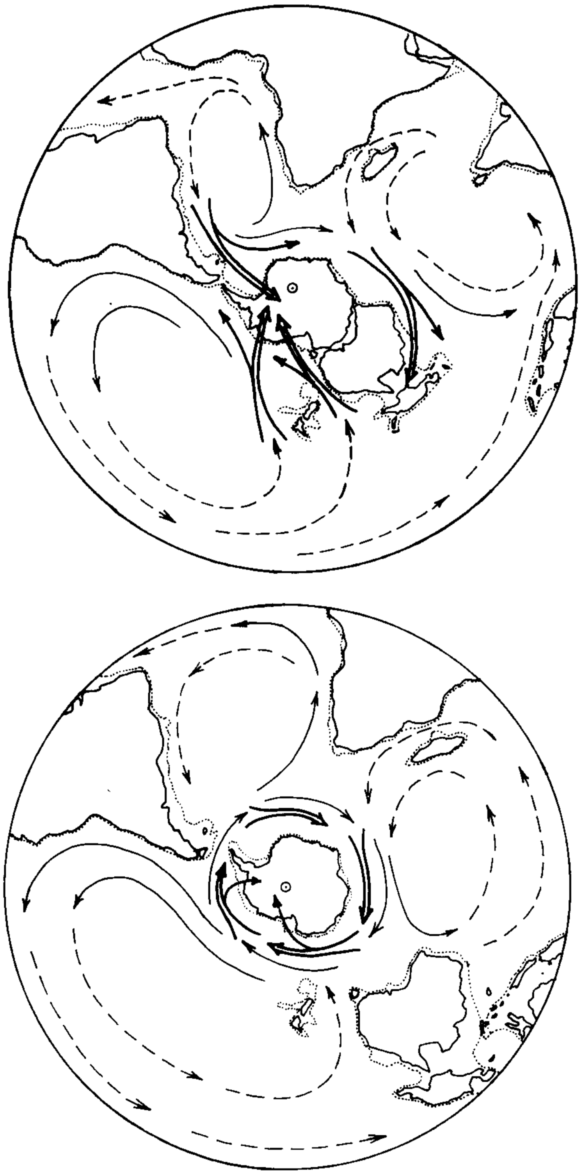

Fig.5. The transformation of ocean and atmospheric circulation in the Antarctic that resulted from continental drift during the Cenozoic. Cyclonic storm tracks, both major (heavy double arrows) and minor (heavy single arrows), and ocean surface currents, both cold (light solid arrows) and warm (light dashed arrows), changed dramatically from the Eocene (top) to the present day (bottom). Eocene circulation brought a warm ocean surface current into West Antarctica and major convective storm systems dumped heavy precipitation over West Antarctica, which was an island archipelago at that time. In present-day circulation, the Antarctic Circumpolar Current prevents warm surface water from reaching West Antarctica, and only minor convective storm systems traverse West Antarctica which is covered by a marine ice sheet. East Antarctica retained a continental climate that is typically cold and dry in polar latitudes. However, East Antarctica was largely unglaciated in the Eocene and today it is nearly covered by a terrestrial ice sheet.

Eocene glaciation

My notion of the glacial history of Antarctica is keyed on the priority of West Antarctic glaciation and is summarized in Figure 6. Eocene glaciation was restricted to a seasonal sea-ice cover in the seas of West Antarctica, particularly on water nearest to the South Pole, and to mountain glaciers in both East and West Antarctica. These conditions reflected ocean and atmospheric circulations affecting West Antarctica that were similar to circulations affecting the Bering Sea and southern Alaska today. Eocene conditions in East Antarctica were similar to conditions in north-east Siberia today.

The transition from Eocene to present-day Antarctic ocean and atmospheric circulations began when rifting isolated Antarctica from Australia and South America (Kennett 1978). A major event in that transition was the progression from sea ice to fast ice to ice shelves to marine ice domes to a marine ice sheet in West Antarctica. Thickening of sea ice to become grounded ice shelves was first accomplished about 37 Ma BP, and gave rise to the cooling event discussed by Kennett (1978). Production of Antarctic Bottom Water would have been prodigious during ice thickening, and could have been the cause of the dramatic cooling in the benthic paleotemperature curve at DSDP Site 277 on the Campbell Plateau.

Oligocene glaciation

Oligocene glaciation in the Ross and Weddell seas of West Antarctica (Fig.6-1) should have been similar to Quaternary glaciation in the Barents and Kara seas of northern Eurasia. The warm South Pacific gyre that entered the Ross Sea 50 Ma BP should have had the same effect as the warm North Atlantic Current that enters the Barents Sea today. The Ellsworth Mountains would have sheltered the Weddell Sea from this current, just as Novaya Zemlya now shelters the Kara Sea. Consequently, formation of marine ice domes from thickening sea ice 37 Ma BP would occur first in the Weddell Sea, probably where the Ronne Ice Shelf lies today, just as the Kara Sea marine ice dome formed first. And, just as formation of the Barents Sea marine ice dome was delayed until the North Atlantic current became directed toward Spain, formation of the Ross Sea marine ice dome was delayed until the Antarctic Circumpolar Current became directed toward Drake Passage about 30 Ma BP.

A floating ice shelf supplied by the Ross and Weddell seas marine ice domes would have spread across Bentley Subglacial Trench and run aground against the islands and mountains of Marie Byrd Land and the Antarctic Peninsula. Thickening and grounding over Bentley Subglacial Trench would then occur, creating a marine ice divide that connected the Ross and Weddell sea domes. Lavas erupting subglacially in Marie Byrd Land (LeMasurier and Wade 1976), and covering a glaciated landscape in the Jones Mountains (Rutford and others 1972), indicate that this ice

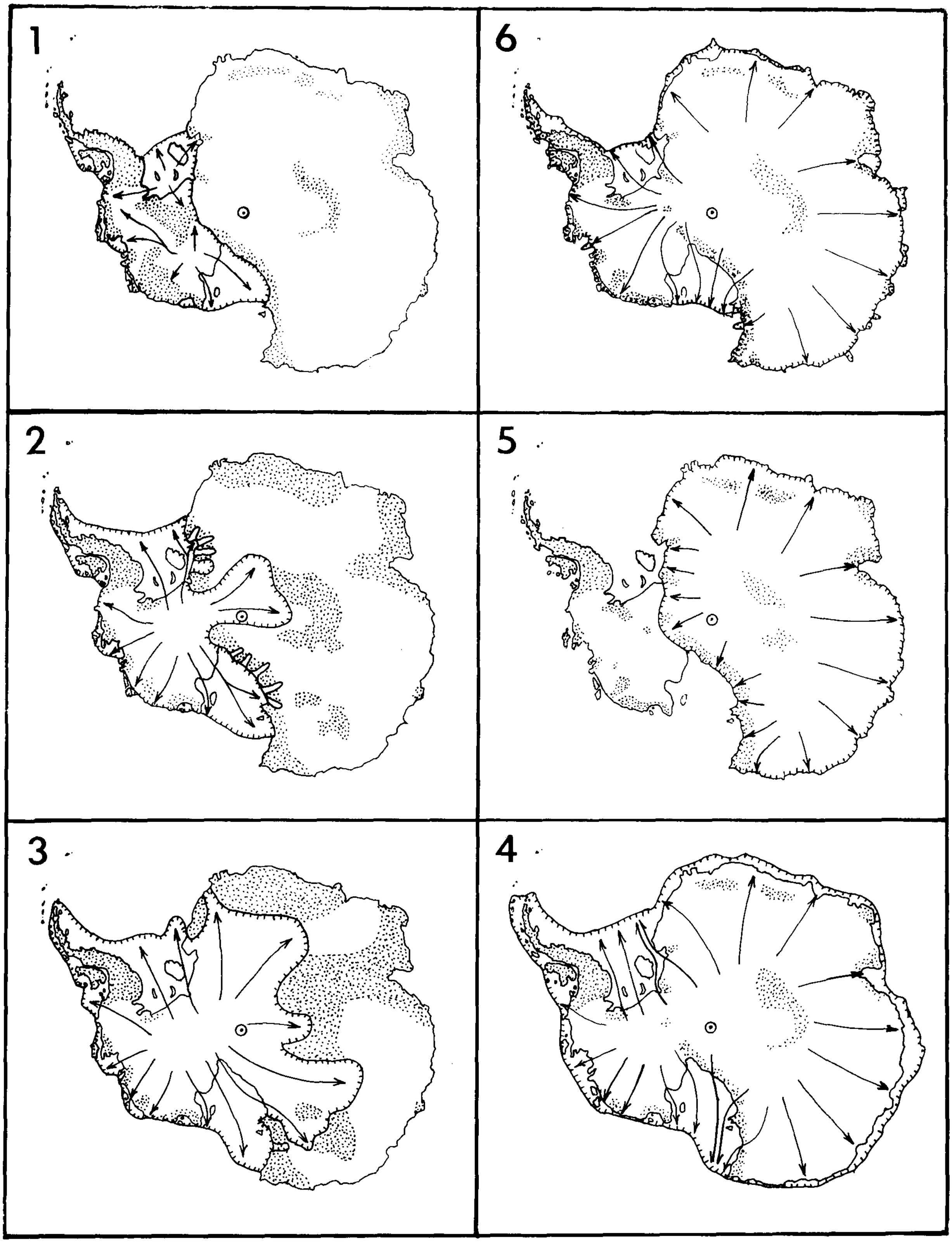

Fig.6. A history of Cenozoic glaciation in Antarctica based on the marine ice transgression hypothesis. Spreading marine ice (arrows) merged with highland centers of terrestrial ice (dotted areas) to establish Cenozoic limits of the Antarctic ice sheet (hachured line), both floating and grounded portions, shown in relation to its present-day grounded portion (solid border). Glaciation is shown for the Oligocene (1), the early Miocene (2), the middle Miocene (3), the late Miocene (4), the Pliocene (5), and the Quaternary (6).

divide was established about 30 Ma BP. Mountain glaciers and terrestrial ice caps in West Antarctica should have merged with the much larger marine ice domes by that time, completing the formation of the West Antarctic ice sheet.

Miocene glaciation

Early Miocene glaciation in Antarctica saw the expansion of the West Antarctic ice sheet southward into East Antarctica and northward toward the continental shelf (Fig.6-2). This expansion began 25 Ma BP, as recorded by ice-rafted sediments deposited at DSDP Site 270 in the Ross Sea (Hayes and Frakes 1975: 929) and DSDP Site 325 in the Bellingshausen Sea (Hollister and others 1976: 171). Ice-rafting at these sites indicates that northward expansion of the West Antarctic ice sheet was in the form of floating ice shelves that spread seaward and calved as tabular icebergs. The early Miocene expansion of West Antarctic ice would have been a consequence of ice thickening that converted the low Oligocene ice sheet having multiple domes into a high Miocene ice sheet having a major central dome over the Whitmore Mountains. Consequently, the early Miocene ice sheet would be similar to the West Antarctic ice sheet today, with a major central dome and a fringe of ice shelves, and the northern Ross Sea (and probably the northern Weddell Sea) would have only a seasonal sea-ice cover. Biological extinctions and oceanographic changes caused by this spreading West Antarctic ice are discussed by Drewry (1978), Kennett (1978), and Mercer (1978), who postulated other causes for these changes.

Middle Miocene glaciation in Antarctica saw a massive advance of West Antarctic marine ice into East Antarctica, where it merged with spreading centers of terrestrial ice to create the East Antarctic ice sheet (Fig.6-3). Depletion of ^{16}O in sub-Antarctic cores from DSDP Leg 29 show that most of the East Antarctic ice sheet formed 14 to 10 Ma BP (Shackleton and Kennett 1975). Both the marine ice advancing from West Antarctica and the native terrestrial ice would be rich in ^{16}O, as required in ice formed by compacted snow compared to ice formed from frozen sea-water. Grounding of West Antarctic ice shelves in the Ross and Weddell seas would allow an explosion of West Antarctic ice into East Antarctica along a 3 000 km front from Terra Nova Bay to the Shackleton Range. The only barrier impeding this influx would have been the Transantarctic Mountains, which were uplifted during the Cenozoic. If most of the uplift has occurred in the last 10 Ma, the invasion of West Antarctic ice would have been largely unchecked and would have diminished the contributions of terrestrial ice on East Antarctic highlands to the formation of the East Antarctic ice sheet. By shrinking or eliminating ablation zones along the front of the advancing ice, global climatic cooling in the middle Miocene (Mercer 1978) would have accelerated the rate of advance.

Late Miocene glaciation in Antarctica saw a consolidation of the Antarctic ice sheet and an expansion to its greatest extent (Fig.6-4). Consolidation began with a change in orientation of the ice divide of West Antarctica from east-west to north-south, reflecting the influx of marine ice into East Antarctica, and it ended when multiple terrestrial ice domes over the various East Antarctic highlands became largely submerged by a major central dome near the South Pole. This high central dome resulted from the merger of the large terrestrial dome over the Gamburtsev Mountains with the invading marine ice from central West Antarctica, and its South Pole location is indicated by the radial pattern of bedrock striations in the Transantarctic Mountains (Mayewski 1975).

Expansion of the Antarctic ice sheet is recorded as a 300 km northward expansion of the siliceous biogenic sediment belt around Antarctica and a rapid northward migration of the Antarctic Convergence (Kemp and others 1975). The expansion of grounded ice continued to the edge of the Antarctic continental shelf (Hayes and Frakes 1975). Whether floating ice shelves extended into deeper water beyond the continental shelf is unknown. This expansion occurred between 10 and 5 Ma BP.

Pliocene glaciation

Pliocene glaciation in Antarctica saw a collapse (Fig.6-5) and reformation (Fig.6-6) of the West Antarctic ice sheet after it reached its maximum extent in the late Miocene. Isostatic sinking of the West Antarctic continental shelf under the ice load, combined with glacial erosion of the interior and glacial deposition around the margins, all over a time span of some 30 Ma, created a concave depression that would eventually make the West Antarctic ice sheet inherently unstable (Weertman 1974, Stuiver and others 1981). The present-day grounded margin of the ice sheet lies on a downhill slope toward the center. Beyond this margin, floating ice shelves are anchored to the sea floor by islands and shoals that project upward into the base of ice shelves, and these pinning points prevent the grounding line from retreating down-slope into the central subglacial basin. Today, the basin beneath the West Antarctic ice sheet is 2 500 m below sea-level on the floor of Bentley Subglacial Trench.

When the West Antarctic ice sheet advanced to the edge of the continental shelf in the late Miocene, it would have absorbed its fringing ice shelves as they became grounded. Without buttressing ice shelves pinned to islands and shoals, the West Antarctic ice sheet may have become unstable just when it seemed to be at its most stable and awesome. Collapse of the West Antarctic ice sheet would have inundated the Southern Ocean with icebergs. This might have triggered the drastic cooling in high southern latitudes from 3.7 to 3.5 Ma BP that Mercer (1978) discussed and attributed to formation, not collapse, of the West Antarctic ice sheet.

Late Pliocene recovery of the West Antarctic ice sheet, following its early Pliocene collapse, may have required the lowering of sea-level that accompanied formation of ice sheets in the northern hemisphere. In any event, recovery was different from the initial formation of the West Antarctic ice sheet during the Oligocene. Neither the concave depression in the West Antarctic continental shelf nor the East Antarctic ice sheet were present in the Oligocene. Northern hemisphere ice sheets that so drastically changed Quaternary sea levels were also absent. A flood of East Antarctic ice into West Antarctica, perhaps lowered onto the continental shelf by falling sea-level during the growth of northern hemisphere ice sheets, would have allowed the West Antarctic ice sheet to reform. Most of the East Antarctic ice would flood into West Antarctica through the gaps between the Pensacola, Thiel, and Horlick mountains, reversing the flow of ice that created the East Antarctic ice sheet and causing the high central East Antarctic ice dome to retreat to a position over the Gamburtsev Mountains.

Drewry (1978) described subglacial troughs through the Transantarctic Mountains that may have been carved by ice streams from East Antarctica when the West Antarctic ice sheet reformed. However, he believed that the West Antarctic ice sheet first formed from East Antarctic ice during the cold period 4 to 5 Ma BP, in the way proposed by Bentley and Ostenso (1961), and that the ice-stream troughs were carved then.

East Antarctic ice would not contribute significantly to recovery of the West Antarctic ice sheet after the Ross and Filchner-Ronne ice shelves became grounded, because most East Antarctic ice flowing into West Antarctica would then be directed into the sea-floor troughs along the north flank of the Transantarctic Mountains, creating two huge ice streams, one in the Ross Sea and one in the Weddell Sea. These

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ice streams would discharge ice beyond the West Antarctic continental shelf, as shown in Figure 6-4.

Quaternary glaciation

Quaternary glaciation in Antarctica has been primarily a history of partial or total collapse and recovery of the West Antarctic ice sheet that is essentially in phase with cycles of northern hemisphere glaciation (Stuiver and others 1981). This is because the West Antarctic ice sheet now shrinks and expands in lock step with the rise and fall of sea-level (Hollin 1962), which accompanies the retreat and advance of northern hemisphere ice sheets. The retreat and advance of these ice sheets, in turn, are triggered by Milankovitch variations of solar radiation caused by cyclic variations in the eccentricity of the Earth's orbit and the tilt and precession of the Earth's rotation axis (Hays and others 1976).

Since glaciations occupy about 90% of the Quaternary on a 0.1 Ma cycle, Figure 6-4 represents the usual state of Quaternary glaciation in Antarctica. The West Antarctic ice sheet is usually in place, with extensive ice shelves forming in the Ross and Weddell embayments during interglaciation episodes, when collapse may be only partial, as shown in Figure 6-6 for the present day interglaciation (Stuiver and others 1981). Total collapse of the kind shown in Figure 6-5 may have occurred during the previous interglaciation about 0.125 Ma BP (Mercer 1968).

ACKNOWLEDGEMENTS

I thank George H Denton for many stimulating discussions on the glacial history of the Arctic and the Antarctic.

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