Journal of Glaciology, Vol. 24, No. 90, 1979

LATE WISCONSIN RECONSTRUCTION FOR THE ROSS SEA REGION, ANTARCTICA

By DAVID J. DREWRY

(Scott Polar Research Institute, Lensfield Road, Cambridge CB2 1ER, England)

ABSTRACT. If sea-level depression in the Ross Sea embayment were: (1) $<$120–130 m, or (2) $>$120–130 m but sustained for $<10^4$ a, it is unlikely that the Ross Ice Shelf would have become fully grounded over the whole continental shelf during Wisconsin times. Sediments flooring the Ross Sea and recent estimates of sea-level lowering and post-glacial emergence yield little support for grounded ice but do provide some evidence for expanded ice-shelf conditions. A reconstruction is presented based on this premise. The model is compatible with glacial geologic results, especially those in the McMurdo Sound area.

RÉSUMÉ. *Reconstitution de la fin du Wisconsin pour la région de la Mer de Ross, Antarctique.* Si l'abaissement du niveau de la mer dans la Mer de Ross était: soit (1) inférieur à 120–130 m soit (2) supérieur à 120–130 m mais maintenu pendant plus de 10 000 ans il est improbable que le Ross Ice Shelf ait du devenir entièrement ancrée au sol sur tout le plateau continental pendant l'époque du Wisconsin. Les sédiments tapissant le fond de la Mer de Ross donnent peu d'indices d'une glace ancrée au sol mais aportent des prémices de l'existence d'une plateforme de glace. Sur ces prémices on présente une reconstitution. Le modèle est compatible avec les résultats de la géologie glaciaire spécialement ceux de la région de McMurdo Sound.

ZUSAMMENFASSUNG. *Rekonstruktion der Rossmeer-Region, Antarktis, im späten Wisconsin.* Wenn die Meeresspiegelsenkung in der Rossmeerbucht entweder weniger als 120–130 m, oder mehr als 120–130 m aber kürzer als 10 000 Jahre, betrug, ist es unwahrscheinlich, dass das Ross Ice Shelf während der Wisconsin-Eiszeit auf dem ganzen Kontinentalschelf völlig aufgesessen ist. Sedimente am Boden des Rossmeeres liefern wenige Hinweise auf aufsitzendes Eis, hingegen gewisse Beweise für eine grössere Ausdehnung des Schelfeises. Unter dieser Prämisse wird eine Rekonstruktion dargeboten. Das Modell stimmt mit glazialgeologischen Ergebnissen überein, besonders mit solchen aus dem Gebiet des McMurdo Sound.

"My opinion is that at or near the time of maximum glaciation the huge glaciers, no longer able to float in a sea of 400 fathoms, joined hands and spread out over the Ross Sea, completely filling it with an immense sheet of ice. At the time the edge of the sheet and the first place at which it could be water-borne bordered on the ocean depths to the north of Cape Adare."

R. F. Scott, R.N. (1905, p. 423)

INTRODUCTION

Northern Hemisphere glacial episodes resulted in major depressions of global sea-level. In Antarctica these would have been responsible for expansion of zones of the ice sheet sensitive to sea-level—principally the grounded marine ice mass in West Antarctica (including flanking ice shelves in the Ross and Weddell Seas). At several times during the Late Cenozoic, ice sheets advanced and grounded over the Ross Sea (e.g. 3–5 Ma B.P. and during the Matuyama reversed magnetic epoch (2.4–0.69 Ma B.P.)), and is documented by marine seismic profiling which shows evidence for truncated bedding; deep-sea cores exhibit marked unconformities and terrestrial glacial deposits attest to former thickening in ice-free terrain bordering the Ross Sea. In this paper, however, we focus on conditions during the last 10^5 a.

T. J. Hughes, G. H. Denton, and co-workers at the University of Maine, and recently R. H. Thomas and C. R. Bentley, have proposed models illustrating conditions in late Wisconsin times and envisage an enlarged and fully grounded ice sheet in the Ross Sea embayment (hereafter referred to as the Maine model). In some cases this ice mass would have possessed a steady-state (equilibrium) surface profile and extended to the continental shelf edge (Hughes, 1973, 1975; Denton and others, 1979). In the belief that this reconstruction represents only one possible and probably extreme case, an alternative working hypothesis will be developed in this paper, which argues for maintenance of an expanded ice-shelf regime over the major part of the Ross Sea throughout most of the last glaciation (Fig. 1).

https://doi.org/10.3189/S0022143000014763 Published online by Cambridge University Press

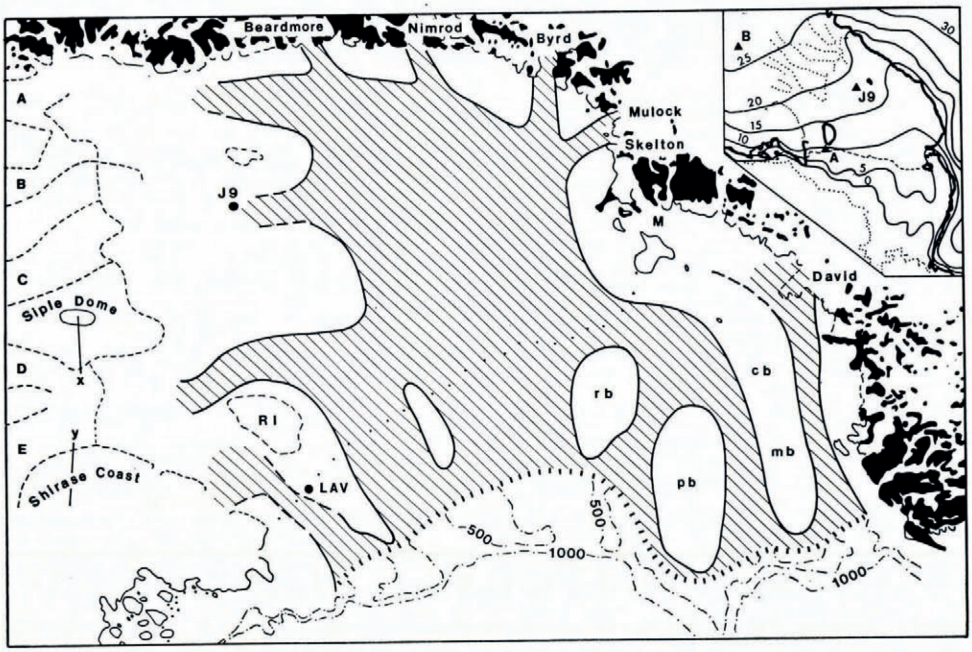

Fig. 1. Reconstruction of Ross Sea embayment during late Wisconsin times (c. *18 ka* B.P.) *showing seaward extension of Ross Ice Shelf and grounding line. Local grounding occurs over submarine banks* (*shown with lower case letters for Crary, Mawson, Pennell, and Ross Banks*), *and adjacent to the Victoria Land Coast. Ice shelf is shaded. Inset depicts part of the Hughes and others* (*1979*) *model: ice-sheet surface contour in* 10^2 *m* (*compare with inset in Fig. 2*). *M = McMurdo Sound; LAV = Little America V; RI = Roosevelt Island. Ice streams in Marie Byrd Land are lettered A–E.*

Several factors are important in determining any reaction of the West Antarctic ice sheet to conditions in the Wisconsin—bathymetry of the Ross Sea, glaciological conditions affecting ice-sheet response, and sea-level depression. A crucial role is played by sea-level fluctuations, both magnitude S_f and duration S_t of any lowering. We find, in common with Thomas and Bentley (1978), that a eustatic sea-level fall of >120–130 m, sustained over a period of 5–10 ka, would fully ground ice in the Ross Sea (the Maine prediction). Although it appears difficult, as yet, to determine with any precision whether sea-level changes met both these threshold conditions, we believe there is little or no substantive evidence for the grounded ice-sheet case but that there is limited support from marine sedimentary studies for the alternative model of an extended ice shelf which is outlined below. If later investigations demonstrate that $S_f > 120–130$ m and $S_t > 5–10$ ka, then our model may be seen as an intermediate situation between the present configuration of the Ross Sea embayment and the Maine reconstruction.

Model constraints

1. *Glaciological factors*

Thickness gradients (dH/dx) and the pattern of flow lines displayed by the present-day Ross Ice Shelf have been used in the 18 ka reconstruction (Fig. 1). Our model argues for maintenance of an ice-shelf regime over the major part of the Ross Sea with forward migration of the ice-shelf grounding line by 300–350 km and commensurate movement of the ice front 150–450 km in order to sustain volume continuity with creep thinning. The mode of ice discharge out of Marie Byrd Land would have been via an arrangement of ice streams. Some variations in their location may well have occurred according to grounding-line position, bottom topography, catchment area, and mass-balance conditions. Since, however, the sea-bed troughs occupied by the ice streams are structurally controlled (Rose, in press; Robertson and others, in press) it is unlikely that their positions would have been drastically modified.

Substantial grounding would have characterized the coastal zone adjacent to Victoria Land assisted here by off-shore islands and shallow submarine banks (Pennell, Crary, and Mawson Banks, Franklin Shoal, Ross, Beaufort, and Franklin Islands) and thick ice contributed from Byrd Glacier. We consider that the enlarged grounded areas especially in western Marie Byrd Land would have been dominated by active, low-gradient ice streams extending several hundred kilometres inland of the grounding line and separated by slow-moving ridges and domes. The pattern would correspond closely with that observed in Marie Byrd Land today (Rose, 1979). Inland of the ice streams, surface slopes may well have been similar to those of other grounded ice sheets of comparable depth. This pattern implies only nominal thickening of the ice sheet and does not seek the substantial change to the overall surface profile demanded by the Maine reconstruction (Fig. 2).

This conclusion is supported by several glaciological investigations in West Antarctica. Along the Byrd Station strain network (BSSN), Whillans (1976) has deduced that the West Antarctic ice sheet has maintained near steady-state conditions (in terms of ice-sheet shape, mass balance, and velocity field) during a minimum of 20 ka. He considers that his conclusions on stability may relate to an area well beyond the BSSN (and even to most of Marie Byrd Land) and is consistent with our postulated thickening.

Tentative interpretation of isotopic and total-gas content of core from Byrd Station (Robin, 1977) suggests a net climatic warming of 5–8 deg since the coldest period of the Wisconsin, and

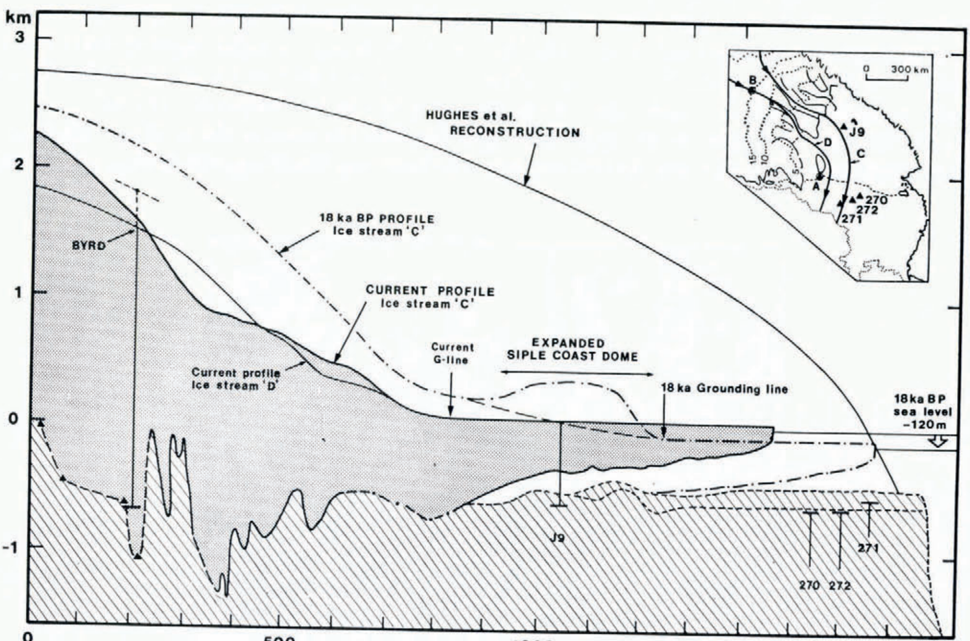

Fig. 2. Inferred profile through expanded ice sheet–ice shelf in the Ross Sea along ice stream C. Comparison with current profile and that proposed by Hughes and others (1979). Surface profile and ice thickness taken principally from radio echo-sounding with triangles from seismic shooting. Sea bed in Ross Sea shows maximum and minimum elevations in a 50 km band of the flow line. Location of DSDP, RISP, and Byrd Station cores are also shown. Current Byrd–ice stream D surface profile shown with 300 m thickening at Byrd Station. Inset shows location of ice-stream flow lines and cores, present-day surface contours in 10^2 m.

https://doi.org/10.3189/S0022143000014763 Published online by Cambridge University Press

an elevation decrease of the ice sheet by 600 m of which about 300 m could be due to down-slope flow. The remaining 300 m may represent an upper limit to the real decrease in ice-sheet thickness, but again compatible with the magnitude of the retreat of the grounding line and the subsequent thinning indicated by our model. This result is clearly divergent from the 1 000 m surface lowering and 1 760 m thinning required by the Maine analysis at Byrd Station (Figs 1 and 2).

2. *Ross Sea bathymetry*

Sea-bed topography in the Ross Sea embayment provides an important base-line against which sea-level changes may trigger ice-sheet–ice-shelf advances and groundings.

Improved knowledge of the configuration of the Ross Sea continental shelf has been embodied into two charts by Hayes and Davey (1975) and Vanney and Johnson (1976). Beneath the Ross Ice Shelf seismic reflection shooting has enabled reconnaissance mapping of the sea bed (Robertson and others, in press). Inland of the Ross Ice Shelf grounding line radio echo-sounding has provided the first detailed study of the ice–rock interface in Marie Byrd Land (Rose, in press).

The important bathymetric elements within the embayment are linear depressions and sub-parallel submarine banks (Fig. 3). The former are currently occupied by ice streams in the grounded (Marie Byrd Land) area (Rose, 1979) but extend out across the shelf at a depth of 500–600 m below sea-level (Robertson and others, in press), rising slightly towards the continental edge. It has been demonstrated that these troughs are structurally controlled basement features (Rose, in press; Robertson and others, in press). A number of shallow banks are present separating depressions. In the western Ross Sea these are clearly linear features parallel to the troughs, but to the east there is some disagreement between the chart of Hayes and Davey and that of Vanney and Johnson (allowing for differences in their contour intervals). In the former case the alternating pattern of shoals and swales is maintained, while the latter depicts a zone of shoals striking across the grain of the suspected troughs.

Important in evaluating bathymetric and sea-level interactions is the isostatic state of the Ross Sea shelf. Early gravity measurements over the Ross Ice Shelf suggested that a −12 mgal

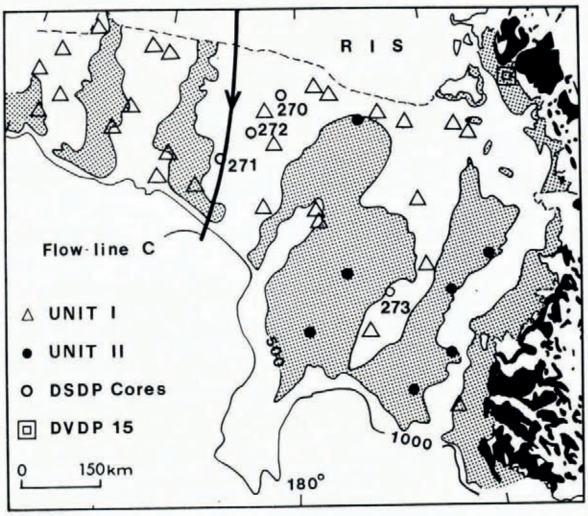

Fig. 3. Location of Eltanin *piston and other rotary cores in the Ross Sea and their relation to bathymetry (in metres below sea-level). Units I and II refer to material exposed on the sea floor; their ages are given in Table I and discussed in the text.*

https://doi.org/10.3189/S0022143000014763 Published online by Cambridge University Press

average free-air anomaly was related to incomplete isostatic adjustment from former ice loading (Bennett, 1964). Additional data are now available on the Ross Ice Shelf (Bentley and others, in press) and for the Ross Sea (Hayes and Davey, 1975). Some of the gravity gradients over the eastern Ross Ice Shelf (15 mgal in 500 km) may indeed be explained by former ice loading, a conclusion consistent with both the Maine model and mine, since both require some further grounding over this part of the Ross Ice Shelf. In the Ross Sea, however, marine free-air gravity data demonstrate little correlation with bathymetry (i.e. none similar to that displayed in North America and Scandinavia where the gravity field often closely mirrors topography (Walcott, 1970)). Such observations would suggest possible influence of other controlling factors such as tectonic activity. Indeed analysis of RIGGS data (Bentley and others, in press) points to such geological influences on the gravity field of the Ross Ice Shelf and indicates that the gravity results cannot be unambiguously interpreted in terms of recent large-scale ice loading. Substantial vertical movements during the mid to late Cenozoic are already documented (Barrett, 1975).

3. *Sea-level*

Crucial factors in all reconstructions of the Ross Sea region are the magnitude and duration of major sea-level changes. A major eustatic sea-level fall (S_f) of >150 m would fully ground and thicken the present Ross Ice Shelf where much of the water column, especially in the eastern sector, is less than 200 m thick (Clough and Robertson, 1975). Since the floor of the now open Ross Sea lies at similar, and over considerable areas at higher, elevations than beneath the shelf, the grounding line would continue to advance towards the continental shelf edge as predicted by Weertman (1974). If $S_f < 50$ m the result would be only a small forward movement of the grounding line (i.e. proportional to bed slope) as the sea floor is sufficiently deep to maintain buoyancy. There is, therefore, a critical value for S_f which will trigger full-scale grounding in the Ross Sea. Based on current ice-shelf thickness gradients and detailed bathymetry we suggest a number between -120 and -130 m. This agrees closely with Thomas and Bentley (1978), whose calculations of thickness for an equilibrium grounding line take into account various values of the sliding-law parameters.

If such a eustatic change were sustained for only a short period, however, an expanding ice sheet might not have sufficient time to achieve equilibrium, and subsequent rising sea-level would trigger premature retreat. The value taken by the duration S_t of sea-level lowering, which has not been stressed in previous studies, is thus of considerable importance, although difficult to estimate. A marine ice sheet buttressed by an ice shelf, may have a complex response depending upon creep and sliding laws, friction between ice shelf and its margins, accumulation-rates within interior catchments, the presence and dynamics of ice streams, etc. In consideration of these factors and the work of Thomas and Bentley (1978), who examine the reverse case of ice-sheet retreat, we suggest that for grounding-line advance across the Ross Sea (a distance of up to 1 000 km) to reach equilibrium, the response time may lie between 10^3 and 10^4 years. Advance-rate is not likely to be linear, but with slow initial forward motion as ice is thin, cold, and possibly frozen to the bed. As it thickens, basal ice will warm and "soften" speeding the advance, with possible development of fast basal sliding and strong preferred fabrics. The process may later slow as interior catchments become starved of accumulation by their increasing separation from moisture sources. The net result of such response times is that the amplitude of short-term sea-level events (e.g. maximum lowering during the late Wisconsin) will be filtered out and hence not experienced by the ice shelf.

It is at present difficult to evaluate precisely the magnitude of sea-level changes in the Ross Sea during Wisconsin times. This is due to the complex interaction between isostatic adjustment in the ocean basins and transient sea-level tilting induced by gravitational attraction of ice masses (Farrell and Clark, 1976; Clark, 1976). Several estimates of the volume of water abstracted by ice during Stage 2 have been given; the most reliable result from stable-isotope analyses of marine cores with high sedimentation rates. Ninkovich and Shackleton (1975) report a change in $\delta^{18}O$ of $-1.6‰$ although earlier studies by Shackleton and Opdyke (1973) suggested a figure of $-1.2‰$. These values represent lowering of sea-level by 160 m and 120 m respectively if we apply the rule-of-thumb: $S_f = 100\delta$ (Shackleton and Opdyke, 1973) although $S_f = 110\delta$ is also used. These figures include the effects of both north and south polar areas, although we expect the "northern" component to dominate.

Calculation of the resulting depression of sea-level transmitted to the Antarctic coastal zone has to take account of global ocean-floor recovery from unloading and gravitational effects induced by first Northern Hemisphere ice-sheet growth and later Antarctic ice thickening. Some estimation of S_f in the Ross Sea embayment with regard to these factors has recently been made. Clark and others (1978), Lingle and Clark (1979), and Clark and Lingle (in press) have computed sea-level lowering around Antarctica caused by Northern Hemisphere ice-sheet growth to be between 75 and 100 m. J. A. Clark (in a personal communication) suggests that a sea-level stand of -120 m in the Ross Sea would represent an extreme lower limit, and in our modelling we have taken this as a maximum case. Furthermore we believe that independent marine geological data provide indirect evidence for $S_f < 130$ to 120 m by giving limited support for ice-shelf conditions but not grounded ice.

Evidence from Ross Sea marine sediments

If ice was fully grounded within the Ross Sea embayment during Wisconsin times, expansion and retreat over the continental shelf would have entrained and redeposited considerable quantities of sea-floor sediments as till-like units. An expanded ice shelf, however, excepting grounded ice rises, would be practically "clean" of debris over the Ross Sea by virtue of basal melting farther-up the flow line, and would contribute little in the way of sediments. Important evidence in evaluating between these alternative models is therefore given by the sedimentary succession in the Ross Sea.

Eltanin piston cores taken from the Ross Sea have been examined by Fillon (unpublished, 1975) and Truesdale and Kellogg (1979). The latter workers have investigated additional core obtained from U.S.C.G.C. *Glacier* (Kellogg and others, 1979). Deep-sea drilling has been undertaken at five locations in the Ross Sea (*Initial Reports*, 1975; Barrett and others, 1976). More recently eleven gravity cores were obtained from beneath the Ross Ice Shelf at J-9 (Webb and others, 1979; Brady and Martin, 1979).

1. *Lithostratigraphy and depositional environment*

The upper sedimentary sequence flooring the Ross Sea, as sampled by piston and rotary cores, comprises three primary units (Table I). Unit I is a soft, soupy, diatomaceous, silty clay, apparently little reworked and containing only a few per cent fraction of sand. The absence of large clasts or granules and abundant diatoms (40% by volume) are particularly significant and argue for little ice rafting in the Ross Sea with prevailing ice-shelf, pack-ice, and/or open-water conditions.

Immediately beneath Unit I there is a clear change to a much stiffer silty claystone containing scattered pebbles and granules (up to 60 mm in size), but with only 2–5% diatoms. Kellogg and others (1979) recognize a thin (0.1–0.5 m) transition zone between Units I and II consisting of a well-sorted sand. The bulk of Unit II is typically a marine till of between 18 and 40 m thickness. There appears to be little or no evidence of reworking: only at Deep Sea Drilling Project (DSDP) Site 273 in the western Ross Sea, do the Project team (*Initial Reports*, 1975) consider that Unit II may have slumped down the edge of Pennell Bank into the flanking sea-floor trough. This is suggested by seismic profiles, bottom topography, a

TABLE I. LITHO- AND CHRONO-STRATIGRAPHY OF ROSS SEA CORES
Dates favoured in this paper are boxed

Unit	*Thickness* m	*Lithology*	*Date*	*Dating technique*	*Environmental interpretation (this paper)*
I	0.2–1.5	Soft silty clay, abundant diatoms (40%). No large clasts, few % sand. Little reworking	Brunhes[1] [Holocene[2] 20–60 ka]	Foraminifera PPS* Diatoms, ^{14}C Sedimentation rates	Slow sedimentation with no typical ice rafting. Ice shelf, pack ice, and/or open water No evidence of grounded ice
[Transition][3]	0.1–0.5	Well-sorted sand	"Late" Pleistocene[3]		Grounding-line retreat
II	18–40	Soft–stiff silty claystone. Some diatoms (2–5%). Scattered pebbles and granules. Little reworking.[1] Much reworking[3]	Pliocene[1] Gauss (2.4–3.4 Ma B.P.)[1] "Late" Pleistocene[3] [130 ka—mid-Brunhes]	Foraminifera PPS Diatoms	Ice-rafted and ice-contact marine till (slumping at DSDP Site 273) Widespread ice shelf and locally grounded ice sheet
			Unconformity[4]		
III	380	Semi-lithified to lithified pebbly-silty claystone. Few diatoms. Scattered clasts	[Upper Miocene to Oligocene[4, 5]]	Foraminifera Bivalves Diatoms PPS	Typical ice-rafted marine till Restricted ice shelf/ice sheet with open-water conditions

[1] Fillon (unpublished, 1975).
[2] Truesdale and Kellogg (1979) [^{14}C date is $7\,360^{+3\,700}_{-2\,500}$ a B.P.].
[3] Kellogg and others (1979).
[4] *Initial Reports* (1975).
[5] Brady and Martin (1979), Webb and others (1979).
* PPS = Palaeomagnetic polarity stratigraphy.

diachronous, mixed diatom fauna, and lack of current activity. The source of materials would be Unit III. A different opinion is held by Kellogg and others (1979), who believe that Unit II has been extensively reworked, a view they support by the apparent recycling of faunal and floral constituents which exhibit fragmentation and silicification.

Between Units II and III there is evidence of a major unconformity, considered to be equivalent to the angular contact observed on seismic-profiler records from the Ross Sea (Houtz and Davey, 1973; Hayes and Davey, 1975). A pronounced increase in lithification occurs across the unconformity to a thick sequence of hard, pebbly silty-claystone which we interpret as a typical marine till. J-9 cores appear to penetrate similar strata to Unit III. Brady and Martin (1979) find evidence from the palaeontological content of the cores for open water conditions with abundant ice rafting.

2. *Chronology*

According to Fillon (1975) the age of Unit I, given by foraminiferal and palaeomagnetic polarity studies, is Brunhes (0–0.69 Ma B.P.) but it is probable that the early Brunhes is absent and the sediments are much younger. Sedimentation rates typical of glacio-marine deposits, and as determined for old sequences in the Ross Sea from recognition of palaeomagnetic events, are 10–20 m Ma^{-1} (Fillon, 1975, 1977). On the basis of these rates the extrapolated age for the observed thickness of Unit I is between 20 and 60 ka B.P. The work of Truesdale and Kellogg (1979) suggests that Unit I could be at least Holocene in part: they present a ^{14}C date of between 5 and 11 ka B.P. on a composite core sample.

The dating of Unit II is not precise. On the grounds of foraminiferal studies and palaeomagnetic polarity stratigraphy, Fillon (1975) has ascribed the sequence to Gauss epoch (2.4–3.4 Ma B.P.). Kellogg and others (1979), however, assert that Fillon's dating is incorrect, and on the basis of three diatom species infer a late Pleistocene age for the uppermost part of Unit II.

Palaeontological investigation of both foraminiferae and bivalves, combined with a well-defined palaeomagnetic polarity stratigraphy, indicate that Unit III spans the period between Oligocene and upper Miocene (25–7 Ma B.P.) (*Initial Reports*, 1975). Brady and Martin (1979) found abundant microfossils (diatoms, silicoflagellates, and benthonic Foraminifera) in J-9 core which they interpret as suggesting a mid-Miocene age for a succession that appears equivalent to Unit III.

3. *Sediment distribution pattern*

Figure 3 indicates the relative age distribution of sediments in the Ross Sea. The youngest materials (Unit I) are concentrated in the linear topographic lows, while older exposed detritus (principally Unit II) occupies, almost without exclusion, the uppermost stratigraphic position on neighbouring swells or highs. Unit I would appear to be thin close to the front of the Ross Ice Shelf, but thickens towards the continental shelf edge.

4. *Discussion*

There is obvious disagreement on the antiquity of Unit II between Fillon (1975) and Kellogg and others (1979). Fillon's Gauss age is most probably too old. The normal magnetic polarity could well be Brunhes not Gauss, and criticism by Kellogg and others of Fillon's foraminiferal interpretations (including the possibility of reworking) appear justifiable. Nevertheless it is also difficult to substantiate the Late Pleistocene age that Kellogg and others base on diatoms alone. Substantial problems of chronostratigraphic resolution are associated with micro-palaeontological dating in high-latitude environments where species diversity is low (and Unit II is demonstrably diatom-poor). Considerable care is required in establishing the age range of a complete assemblage—it is rarely sufficient to use one or two "key" species by themselves. Although at this time supplementary, independent, datable evidence, is not available to refine Unit II age beyond Brunhes, several other factors lead this writer to believe that Unit II is older than Wisconsin.

Gravity cores taken at J-9 from the sea floor beneath the Ross Ice Shelf (Figs 1 and 2) disclose an extremely thin (few mm) lag deposit overlying compact marine mud containing small erratic pebbles and a high percentage of glacial flour (Webb and others, 1979; Brady and Martin, 1979). The latter unit has been dated on the basis of diatom assemblages and comparison with DSDP and DVDP core materials to the mid-Miocene (*c.* 14 Ma B.P. or Unit III correlative). There is a pronounced absence of a more recent, less-consolidated, reworked layer above Miocene strata. According to the Maine model (Fig. 1 inset) J-9 must have witnessed substantial thickening and grounding of the ice shelf in Wisconsin times.

In common with areas to the north in the now open Ross Sea, Kellogg and others (1979) suggest that such events would have produced a distinctive till-like layer (Unit II).

The findings at J-9 are better explained by assuming Unit II is older than Wisconsin and adopting the expanded-ice-shelf model presented in this paper. Figure 1 indicates that J-9 lies very close to the inferred Late Wisconsin grounding line, but that since it occupies one of the sea-floor troughs it may have been the site of an ice stream. In the brief period when the grounding line was at its maximum seaward extent, this ice stream was probably responsible for active erosion of sea-bed sediments close to J-9. Subsequent grounding-line retreat would have heralded a much longer period with floating ice-shelf conditions over the J-9 site. Debris-poor basal shelf ice, "cleaned" by melting, combined with bottom-current scour, would have suppressed heavy sedimentation, giving rise to the observed thin pebble pavement. Our reconstruction does not, therefore, anticipate a thick Unit II till at J-9. Furthermore the distribution of sediments over the whole Ross Sea area with youngest materials in the topographic lows provides little support for the idea of ice universally grounded in the embayment, let alone the contention that a "Ross Ice Sheet" was responsible for the erosion of distinctive sea-floor channels out to the edge of the continental shelf during the last glaciation. It should also be noted that where the youngest deposits appear to be located on shoals (Fig. 3) these areas lie close to the edge of the continental shelf where local grounding of an expanded ice shelf was not predicted (Fig. 1).

A more reasonable age for Unit II is derived by attributing it to one or more of the several pre-Wisconsin glacial episodes during Brunhes times. Shackleton and Opdyke (1973), for instance, document seven or eight glacials during this period. Furthermore their stable-isotope studies reveal that some of these glacial events were longer and more severe than the Wisconsin. Stages 6, 12(?), and 16–18 appear the most favourable in terms of duration and inferred ice volumes and sea-level lowering for the grounding of ice in the Ross Sea and reworking of sea-floor sediments into Unit II till. They date as approximately 128–195 ka B.P., 440–472 ka B.P., and 592–688 ka B.P. respectively (Shackelton and Opdyke, 1973).

We conclude that sedimentary evidence currently available does not support extensive grounded ice over the Ross Sea but gives tacit confirmation of enlarged ice-shelf conditions in Wisconsin times. It is likely that a concentrated investigation of Ross Sea marine deposits especially beneath the ice shelf may eventually provide the best independent test of Wisconsin glacial models of the region, and programmes addressing this problem should be actively encouraged.

McMurdo Sound region

Considerable glacial geologic investigation has taken place in the McMurdo Sound area. G. H. Denton and co-workers have recognized the westward advance of ice tongues into the dry valleys of southern Victoria Land on the basis of the presence of "fresh" erratics and moraines draped over the flanks of coastal mountains, islands, and entering the valley mouths (Denton and others, 1971; Denton and Borns, 1974).

It is clear that ice with a thickness of between 1–1.3 km was grounded in McMurdo Sound (Denton and others, 1971, but note also the earlier suggestion of 1.2 km ice thickening by David and Priestley, 1914). This is demonstrated by deformation of sediments below 13 m (Unit 2) in Dry Valley Drilling Project (DVDP) hole 15 (Barrett and others, 1976). Although the age of the disconformity between their Units 1 and 2 is not yet known precisely, the presence of recent fossils would suggest that the upper Unit was deposited during the last few thousand years (Barrett and others, 1976) and that deformation should be attributed to a late Wisconsin stage. The grounding in the deep water of McMurdo Sound was appreciably assisted by the geography of the area (possessing numerous peninsulas, promontories, and off-shore islands and shoals). This topographic setting, however, makes interpretation of past events more complicated and it is clearly difficult to extrapolate glacial conditions over the entire Ross Sea embayment on the basis of McMurdo Sound evidence alone.

Lingle and Clark (1979) present sea-level emergence curves for McMurdo Sound following a collapse of a late Wisconsin ice sheet. Their calculations are based on the Maine reconstruction of ice conditions in Antarctica at 18 ka B.P. Net emergence of *c.* 25 m during the last 5 ka is predicted. Some check on sea-level changes is available in McMurdo Sound, where deltas, once graded to local sea-level near Marble Point and New Harbour, are now up to 12.5 m above present sea-level. Shells within the delta sediments have been dated to between 4 620 and 6 350 a B.P. by ^{14}C (Denton and others, 1975; Stuiver and others, 1976). The difference between the predicted and observed, though minimum, emergence might suggest, given the suitability of the Farrell–Clark sea-level algorithm, that the Maine reconstructed ice thickness for this area is in error by a factor of two.

In our reconstruction we have taken into consideration the evidence presented by Denton and others and that from DVDP results for grounded ice in McMurdo Sound. We do not, however, accept that grounding was consequent upon the westward intrusion of an ice sheet from the eastern Ross Sea. We envisage the following events as shown in Figure 4. The major Byrd–Mulock–Skelton Glaciers (BMS) lobe within the Ross Ice Shelf pushed north and slightly west towards Minna Bluff in response to sea-level-induced ice-shelf expansion. The result was the deflection of some of the ice of BMS lobe into McMurdo Sound through the deep channel of White Basin (between White and Ross Islands). The elevated glacial benches of these islands and possible striations at Observation Hill attest to flow in this direction. The ice,

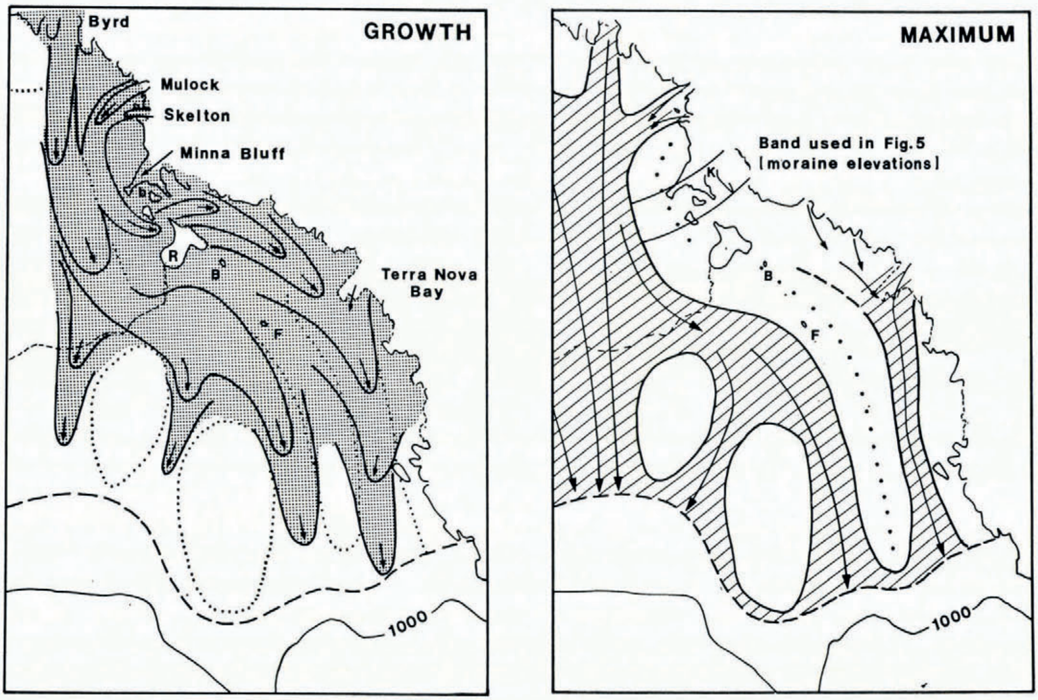

Fig. 4. Schematic reconstruction of conditions in the western Ross Sea during the Wisconsin. Left-hand figure illustrates sequential expansion of ice shelf over the Ross Sea as thick lobes principally from Byrd, Mulock, and Skelton Glaciers. Notice the ice entering McMurdo Sound from the west. The right-hand figure indicates a ridge developed along the south Victoria Land coast and over Crary and Mawson submarine banks flanked by the Byrd and David ice streams. The ice-shed is marked by dots. B is Beaufort Island; b, Black Island; F, Franklin Island; K, Koettlitz Glacier; R, Ross Island.

https://doi.org/10.3189/S0022143000014763 Published online by Cambridge University Press

entering the confines of McMurdo Sound, would have quickly grounded with only weak northward through-flow being maintained—an interpretation supported by only minor intrusion of ice into the dry valleys.

The complex Franklin Shoal area to the north of Ross Island would have become progressively grounded by the lateral transgression of the powerful Byrd ice stream east of Ross Island and slowly expanding McMurdo ice (Fig. 4). Such ice-stream migration would have been responsible for emplacing the erratics discovered by Denton and others (1975) on Beaufort and Franklin Islands. These materials (mainly a Transantarctic Mountains assemblage of granite, dolerite, and sandstone) are probably reworked from deposits brought into McMurdo Sound by Koettlitz, Blue, and Ferrar Glaciers or by BMS lobe itself.

The pattern of grounding in McMurdo Sound (Fig. 4) is compatible with the elevations and geographic distribution of the glacial deposits recognized by Denton and others (1971). Figure 5 shows the height of moraines along an east–west band in McMurdo Sound (Fig. 4) and includes the slope of moraines along Minna Bluff. In our model we postulate that the slope imparted to these deposits resulted from the collapse of a slightly asymmetric ridge with an ice divide lying close to the eastern end of Minna Bluff (Fig. 4). Towards the east the ridge would be buttressed by the Byrd Glacier ice stream. The inset figure in Figure 5 demonstrates that the ridge was a stable feature conforming to the height/width relationship currently exhibited by Antarctic ice domes and ridges. The additional ice surface slopes shown in Figure 5 illustrate two sample cases of comparable ridges and domes flanking ice streams in West Antarctica today.

To the north of McMurdo Sound, ice-shelf extension and local grounding continued. Ice flow out of the major East Antarctic outlet glaciers became restricted. Mawson and David Glacier ice was forced northwards (rather than east into an open Ross Sea) in the form of a powerful ice stream located between ice grounded along the Victoria Land coast and that over the Crary and Mawson submarine banks (Fig. 4). The north-north-easterly deflection of these

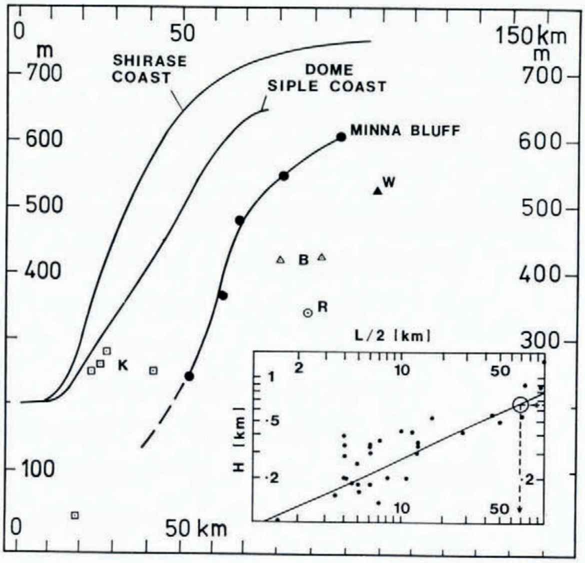

Fig. 5. Ice-sheet surface slopes flanking ice streams in Marie Byrd Land (see sections marked x and y in Fig. 1) and comparison with slope of moraines along Minna Bluff (after Denton). Height of moraines and erratics in adjacent parts of McMurdo Sound are also shown (W, White Island; B, Black Island; R, Ross Island; K, Koettlitz Glacier area; see Fig. 4). Inset: Height versus half-width of Antarctic ice domes and ridges. Fitted line has been used to predict width of the McMurdo Sound ridge shown in Figure 4.

https://doi.org/10.3189/S0022143000014763 Published online by Cambridge University Press

glaciers as an ice stream is clearly shown by the substantial channels cut into the continental shelf (Nordenskiold and Drygalski Basins) which trend obliquely to the present outflow directions (Vanney and Johnson, 1976). The shallowing of these channels to the north demonstrates the weakening of basal erosion as ice gradually decoupled to form ice shelf and approached the late Wisconsin frontal zone.

REFERENCES

Barrett, P. J. 1975. Textural characteristics of Cenozoic preglacial and glacial sediments at Site 270, Ross Sea, Antarctica. *Initial Reports of the Deep Sea Drilling Project*, Vol. 28, p. 757–67.

Barrett, P. J., *and others*. 1976. Dry Valley Drilling Project, 1975–76: first core drilling in McMurdo Sound, [by] P. J. Barrett, S. B. Treves, C. G. Barnes, H. T. Brady, S. A. McCormick, N. Nakai, J. S. Oliver, and K. J. Sillars. *Antarctic Journal of the United States*, Vol. 11, No. 2, p. 78–80.

Bennett, H. F. 1964. A gravity and magnetic survey of the Ross Ice Shelf area, Antarctica. *University of Wisconsin. Geophysical and Polar Research Center. Dept. of Geology. Research Report Series*, No. 64-3.

Bentley, C. R., *and others*. In press. Isostatic gravity anomalies on the Ross Ice Shelf, Antarctica, by C. R. Bentley, J. D. Robertson, and L. L. Greischar. (*In* Craddock, C., *ed. Antarctic geoscience. Proceedings of the third Symposium on Antarctic Geology and Geophysics, Madison, 22–27 August, 1977.* Madison, University of Wisconsin Press.)

Brady, H., *and* Martin, H. 1979. Ross Sea region in the middle Miocene: a glimpse of the past. *Science*, Vol. 203, No. 4379, p. 437–38.

Clark, J. A. 1976. Greenland's rapid postglacial emergence: a result of ice–water gravitational attraction. *Geology*, Vol. 4, No. 5, p. 310–12.

Clark, J. A., *and* Lingle, C. S. In press. Relative sea-level changes caused by retreat of the Antarctic ice sheet during the last 18,000 years. *Quaternary Research.*

Clark, J. A., *and others*. 1978. Global changes in postglacial sea level: a numerical calculation, by J. A. Clark, W. E. Farrell, and W. R. Peltier. *Quaternary Research*, Vol. 9, No. 3, p. 265–87.

Clough, J. W., *and* Robertson, J. D. 1975. RISP geophysical survey. *Antarctic Journal of the United States*, Vol. 10, No. 4, p. 153–55.

David, T. W. E., *and* Priestley, R. E. 1914. *Glaciology, physiography, stratigraphy, and tectonic geology of south Victoria Land.* London, William Heinemann. (Reports on the Scientific Investigations of the British Antarctic Expedition, 1907–9. Geology, Vol. 1.)

Denton, G. H., *and* Borns, H. W., *jr*. 1974. Former grounded ice sheets in the Ross Sea. *Antarctic Journal of the United States*, Vol. 9, No. 4, p. 167.

Denton, G. H., *and others*. 1971. The late Cenozoic glacial history of Antarctica, [by] G. H. Denton, R. L. Armstrong, and M. Stuiver. (*In* Turekian, K. K., *ed. The late Cenozoic glacial ages.* New Haven and London, Yale University Press, p. 267–306.)

Denton, G. H., *and others*. 1975. Glacial history of the Ross Sea, [by] G. H. Denton and H. W. Borns, Jr, M. G. Grosswald [i.e. Grosval'd], M. Stuiver, R. L. Nichols. *Antarctic Journal of the United States*, Vol. 10, No. 4, p. 160–64.

Denton, G. H., *and others*. 1979. Reconstruction and disintegration of ice sheets for the CLIMAP 18 000 and 125 000 years B.P. experiments: results, by G. H. Denton, T. J. Hughes, J. L. Fastook, D. H. Schilling, and C. S. Lingle. *Journal of Glaciology*, Vol. 24, No. 90, p. 495–96.

Farrell, W. E., *and* Clark, J. A. 1976. On postglacial sea level. *Geophysical Journal of the Royal Astronomical Society*, Vol. 46, No. 3, p. 647–67.

Fillon, R. H. 1975. Late Cenozoic paleo-oceanography of the Ross Sea, Antarctica. *Geological Society of America. Bulletin*, Vol. 86, No. 6, p. 839–45.

Fillon, R. H. 1977. Ice-rafted detritus and paleotemperature: late Cenozoic relationships in the Ross Sea region. *Marine Geology*, Vol. 25, Nos. 1–3, p. 73–94.

Fillon, R. H. Unpublished. Late Cenozoic geology, paleo-oceanography, and paleoclimatology of the Ross Sea, Antarctica. [Ph.D. thesis, University of Rhode Island, 1973.]

Hayes, D. E., *and* Davey, F. J. 1975. A geophysical study of the Ross Sea, Antarctica. *Initial Reports of the Deep Sea Drilling Project*, Vol. 28, p. 887–907.

Houtz, R., *and* Davey, F. J. 1973. Seismic profiler and sonobuoy measurements in Ross Sea, Antarctica. *Journal of Geophysical Research*, Vol. 78, No. 17, p. 3448–68.

Hughes, T. J. 1973. Is the West Antarctic ice sheet disintegrating? *Journal of Geophysical Research*, Vol. 78, No. 33, p. 7884–910.

Hughes, T. J. 1975. The West Antarctic ice sheet: instability, disintegration, and initiation of ice ages. *Reviews of Geophysics and Space Physics*, Vol. 13, No. 4, p. 502–26.

Initial Reports. 1975. *Initial Reports of the Deep Sea Drilling Project*, Vol. 28.

Kellogg, T. B., *and others*. 1979. Late Quaternary extent of the West Antarctic ice sheet: new evidence from Ross Sea cores, by T. B. Kellogg, R. S. Truesdale, and L. E. Osterman. *Geology*, Vol. 7, No. 5, p. 249–53.

Lingle, C. S., *and* Clark, J. A. 1979. Antarctic ice-sheet volume at 18 000 years B.P. and Holocene sea-level changes at the West Antarctic margin. *Journal of Glaciology*, Vol. 24, No. 90, p. 213–30.

Ninkovich, D., *and* Shackleton, N. J. 1975. Distribution, stratigraphic position, and age of ash layer "L", in the Panama Basin region. *Earth and Palentary Science Letters*, Vol. 27, No. 1, p. 20–34.

Robertson, J. D., *and others*. In press. Sea bottom topography and crustal structure below the Ross Ice Shelf, Antarctica, by J. D. Robertson, C. R. Bentley, J. W. Clough, and L. L. Greischar. (*In* Craddock, C., *ed. Antarctic geoscience. Proceedings of the third Symposium on Antarctic Geology and Geophysics, Madison, 22–27 August, 1977*. Madison, University of Wisconsin Press.)

Robin, G. de Q. 1977. Ice cores and climatic change. *Philosophical Transactions of the Royal Society of London*, Ser. B, Vol. 280, No. 972, p. 143–68.

Rose, K. E. 1979. Characteristics of ice flow in Marie Byrd Land, Antarctica. *Journal of Glaciology*, Vol. 24, No. 90, p. 63–75.

Rose, K. E. In press. Radio echo studies of bedrock in Marie Byrd Land, Antarctica. (*In* Craddock, C., *ed. Antarctic geoscience. Proceedings of the third Symposium on Antarctic Geology and Geophysics, Madison, 22–27 August, 1977*. Madison, University of Wisconsin Press.)

Scott, R. F. 1905. *The voyage of the "Discovery"*. London, John Murray. 2 vols.

Shackleton, N. J., *and* Opdyke, N. D. 1973. Oxygen isotope and palaeomagnetic stratigraphy of equatorial Pacific core V28-238: oxygen isotope temperatures and ice volumes on a 10^5 and 10^6 year scale. *Quaternary Research*, Vol. 3, No. 1, p. 39–55.

Stuiver, M., *and others*. 1976. Carbon-14 dates of *Adamussium colbecki* (Mollusca) in marine deposits at New Harbor, Taylor Valley, [by] M. Stuiver, G. H. Denton, and H. W. Borns, Jr. *Antarctic Journal of the United States*, Vol. 11, No. 2, p. 86–88.

Thomas, R. H., *and* Bentley, C. R. 1978. A model for Holocene retreat of the West Antarctic ice sheet. *Quaternary Research*, Vol. 10, No. 2, p. 150–70.

Truesdale, R. S., *and* Kellogg, T. B. 1979. Ross Sea diatoms: modern assemblage distributions and their relationship to ecologic, oceanographic, and sedimentary conditions. *Marine Micropaleontology*, Vol. 4, No. 1, p. 13–31.

Vanney, J. R., *and* Johnson, G. L. 1976. Floor of the Ross Sea and adjacent oceanic provinces. *Antarctic Journal of the United States*, Vol. 11, No. 4, p. 231–33.

Walcott, R. I. 1970. Isostatic response to loading of the crust in Canada. *Canadian Journal of Earth Sciences*, Vol. 7, No. 2, Pt. 2, p. 716–27.

Webb, P. N., *and others*. 1979. Miocene glaciomarine sediments from beneath the southern Ross Ice Shelf, Antarctica, [by] P. N. Webb, T. E. Ronan, Jr, J. H. Lipps, [and] T. E. DeLaca. *Science*, Vol. 203, No. 4379, p. 435–37.

Weertman, J. 1974. Stability of the junction of an ice sheet and an ice shelf. *Journal of Glaciology*, Vol. 13, No. 67, p. 3–11.

Whillans, I. M. 1976. Radio-echo layers and the recent stability of the West Antarctic ice sheet. *Nature*, Vol. 264, No. 5582, p. 152–55.

DISCUSSION

C. R. Bentley: Your interpretation of the ocean cores seems to depend rather importantly on the sedimentation rate that you assume. If you increase the sedimentation rate above what appears to be a rather low value, could you not have all the sedimentation taking place after a grounded ice-sheet had removed all the material above the Miocene level?

R. H. Thomas: I would agree with your estimate of approximately 120 m for the critical drop in sea-depth necessary to allow an enlarged West Antarctic ice sheet to cross the Ross Sea. I suggest, however, that the evidence of preferred deposition of recent sediments in the bed troughs is inconclusive evidence for only minor advance of the ice sheet. A collapsing enlarged ice sheet would retreat preferentially up these channels and they would be the first to receive recent marine deposits. Since we do not really know what ice streams do to their beds, it may be premature to speculate about what we expect to find underneath the recent deposits. Finally, if a greatly enlarged West Antarctic ice sheet did cover the Ross Sea during the Wisconsin, most of the retreat to its present day dimensions could have been achieved by 6 000 B.P. (Thomas and Bentley, 1978) and there may be no evidence of this collapse in existing ice cores.

D. J. Drewry: As discussed in the paper, the sedimentation rate (10 m per million years) was chosen as being typical of ice-rafted deposition adjacent to glacier and ice sheets or ice shelves. The crucial factor, however, in answer to both your questions is the absence of any clearly identifiable till horizon attributable to Wisconsin grounding and collapse between the very recent sediments (possibly Holocene from Kellogg's work) and the lithified, undisturbed Miocene–Pliocene sequence. It appears inconceivable that an ice sheet grounded over the Ross Sea would not have:

(1) caused identifiable deformation of underlying sediments (which is demonstrated at DVDP hole 15 in McMurdo Sound),
(2) entrained materials at the bed, and
(3) subsequently released these sediments upon retreat.

We also possess, in answer to Thomas's point, significant information demonstrating that ice streams entrain thick sequence of debris, slide over their beds, and produce thick till layers. Bellair and others (1964) observed the calving and overturning of a large iceberg from Glacier de l'Astrolabe in Terre Adélie. The sole of the berg revealed a considerable layer of wet deformable till, grooved by its passage over bedrock prior to flotation and calving.

T. J. Hughes: G. H. Denton would of course disagree with your interpretation of his published data because he has unpublished data which convince him that a local ice dome near Ross Island is impossible. T. B. Kellogg will soon be publishing his micropalaeontological data from Ross Sea sediments that lead him to the conclusion that a grounded ice sheet extended to the continental shelf margin in later Wisconsin time.

Drewry: I would welcome the rapid publication of this new work which may help to resolve the question of conditions 18 000 a b.p. in the Ross Sea. It is my understanding, however, from conversations with George Denton and his glacial geologic colleagues, that his unpublished work, while presenting a good case for grounding in southern Victoria Land (as also required in my model), cannot distinguish between this complex pattern of local grounding and full-scale expansion over the Ross Sea.

If the work of Kellogg can demonstrate that there are sedimentary till-like materials of late Wisconsin age beneath the upper recent sediments (showing no indication of ice rafting involving coarse debris) then we may begin to entertain the idea of large-scale grounding. As I understand it, his new evidence principally points to a younger age for till of Brunhes materials. [*Note added in proof:* Since the symposium in Ottawa, the paper by Kellogg and others has been published and it is cited and discussed in the paper published in these proceedings.]

G. S. Boulton: I would like to support Dr Drewry's contention that the sedimentary record in the Ross Sea is incompatible with the existence of a grounded ice sheet in the Ross Sea during the Wisconsin. From the rapidly growing amount of data on marine sedimentation beyond the margins of grounded glaciers at the present day, it is almost inconceivable that no sedimentary record should be left behind in the Ross Sea if it had been occupied by a grounded ice sheet.

Bentley: Your model of grounding on banks in the Ross Sea appears to make it difficult to maintain floating ice in between, particularly at Site 273 which is almost completely surrounded by grounded ice. Is there any difference between evidence at Site 273 and the other sites, at which it would appear much easier to keep the ice afloat?

Drewry: Site 273 is different from other DSDP cores only in as much as there appears to be evidence in Unit II of slumping down the western slopes of Pennell Bank. Unit I is typically 0.8 m thick with a sharp colour and lithological break to Unit II. I would point out that our reconstruction is only for transient maximum conditions. At other times, with higher sea-levels, it would be easier to maintain floating ice between ice rises.

REFERENCE

Bellair, P., *and others*. 1964. Un échantillon de moraine interne du Glacier de l'Astrolabe (Terre Adélie), par P. Bellair, J. Tourenq, et S. Vernhet. *Revue de Géographie Physique et de Géologie Dynamique*, Sér. 2, Vol. 6, Fasc. 2, p. 115–21.